Introduction to Mobile Communications Systems

Cellular Concepts

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  - Traffic Engineering
- Essential Concepts at Signal Processing and Transmission Level
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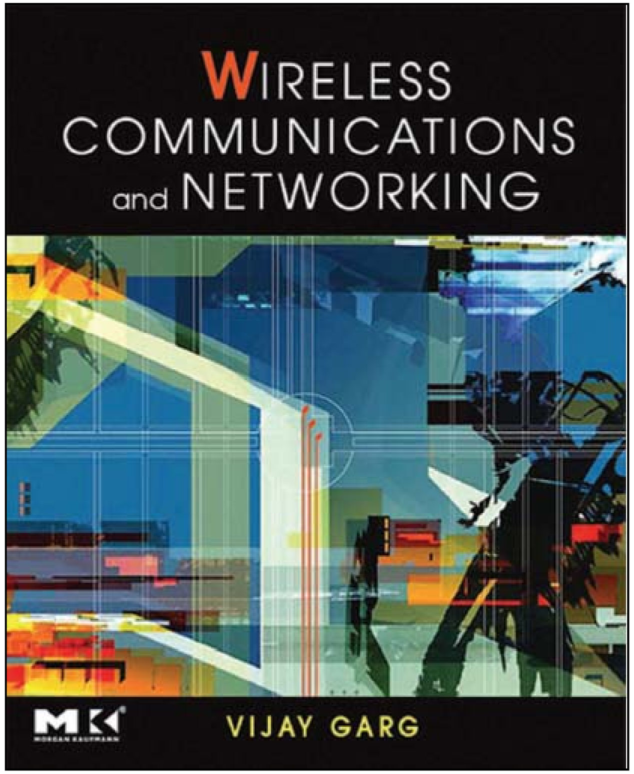
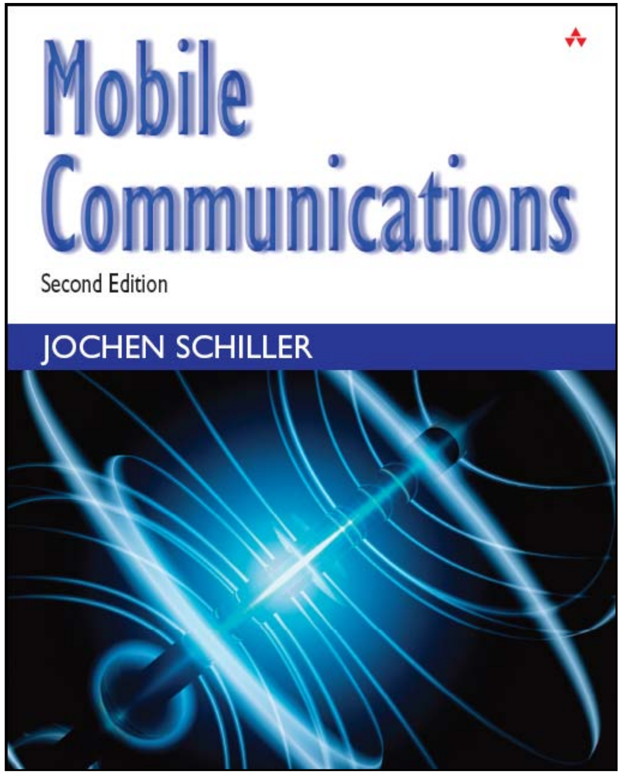
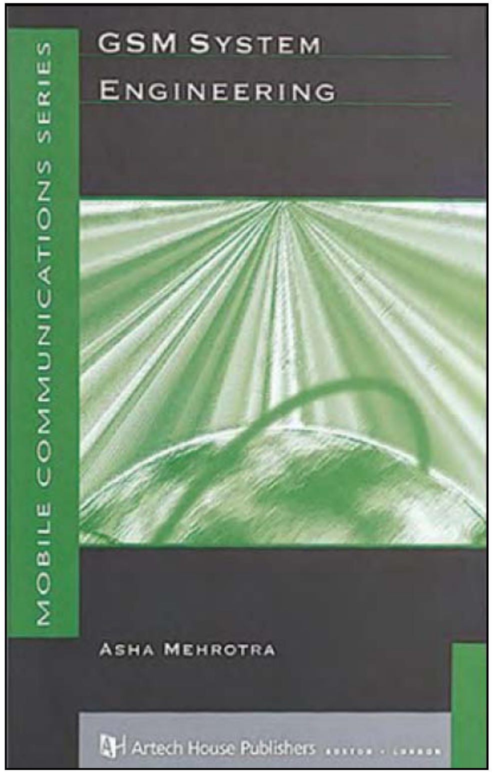
  - Modulation
- Basic System Aspects
  - System Components
  - Security functions
- 3rd Generation Mobile Communications Systems
  - CDMA principles
  - UMTS System Components
  - CDMA specific aspects (Power control, Cell Breathing, RAKE receiver, Handover Types, etc.)
  - Basics of protocol architectures

References

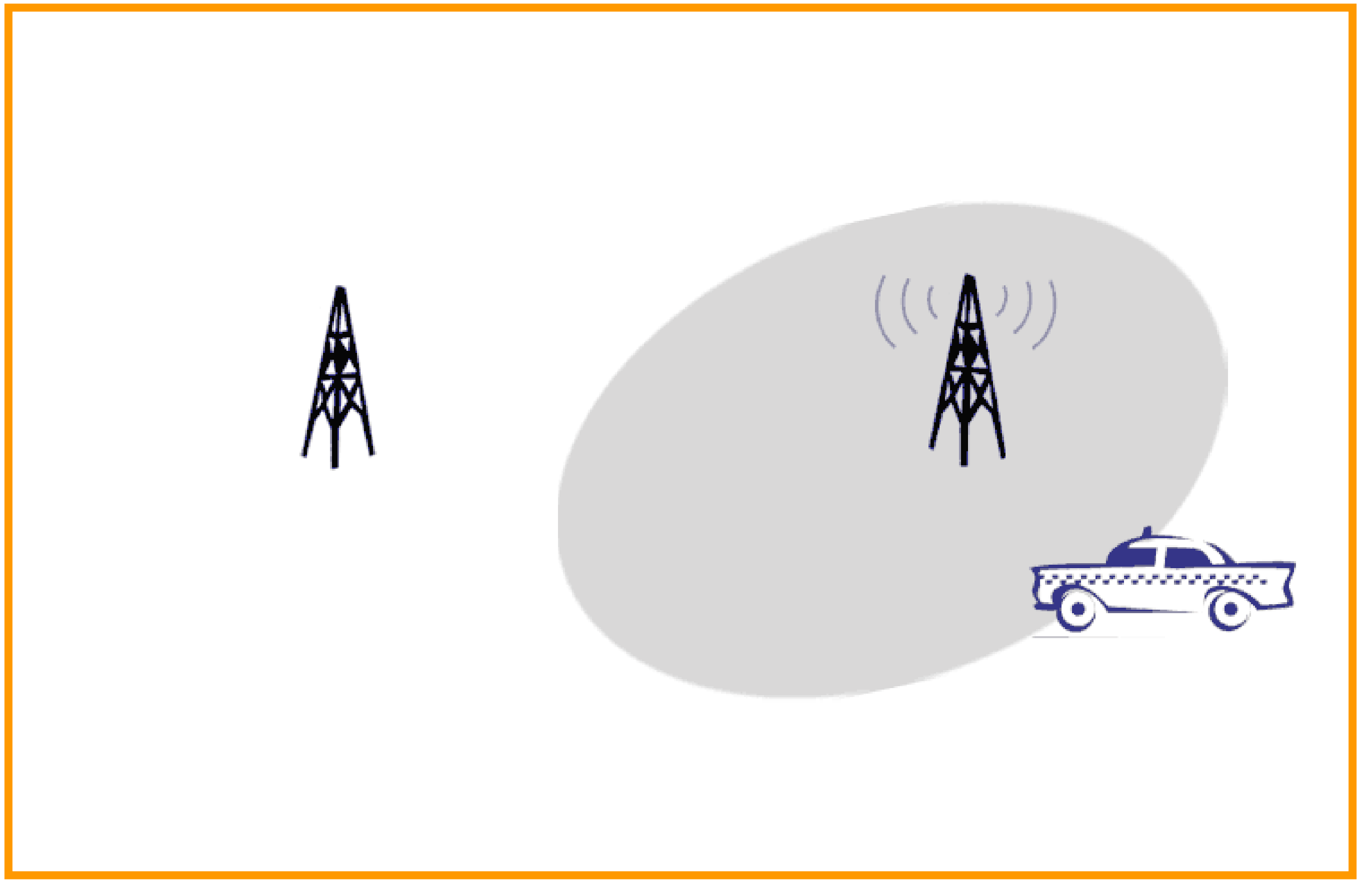






- Additional selected reading material will be provided on demand

Mobile Networks Simplified
Defining Mobility



Mobile Networks Simplified
Basic Services of Telephone Networks

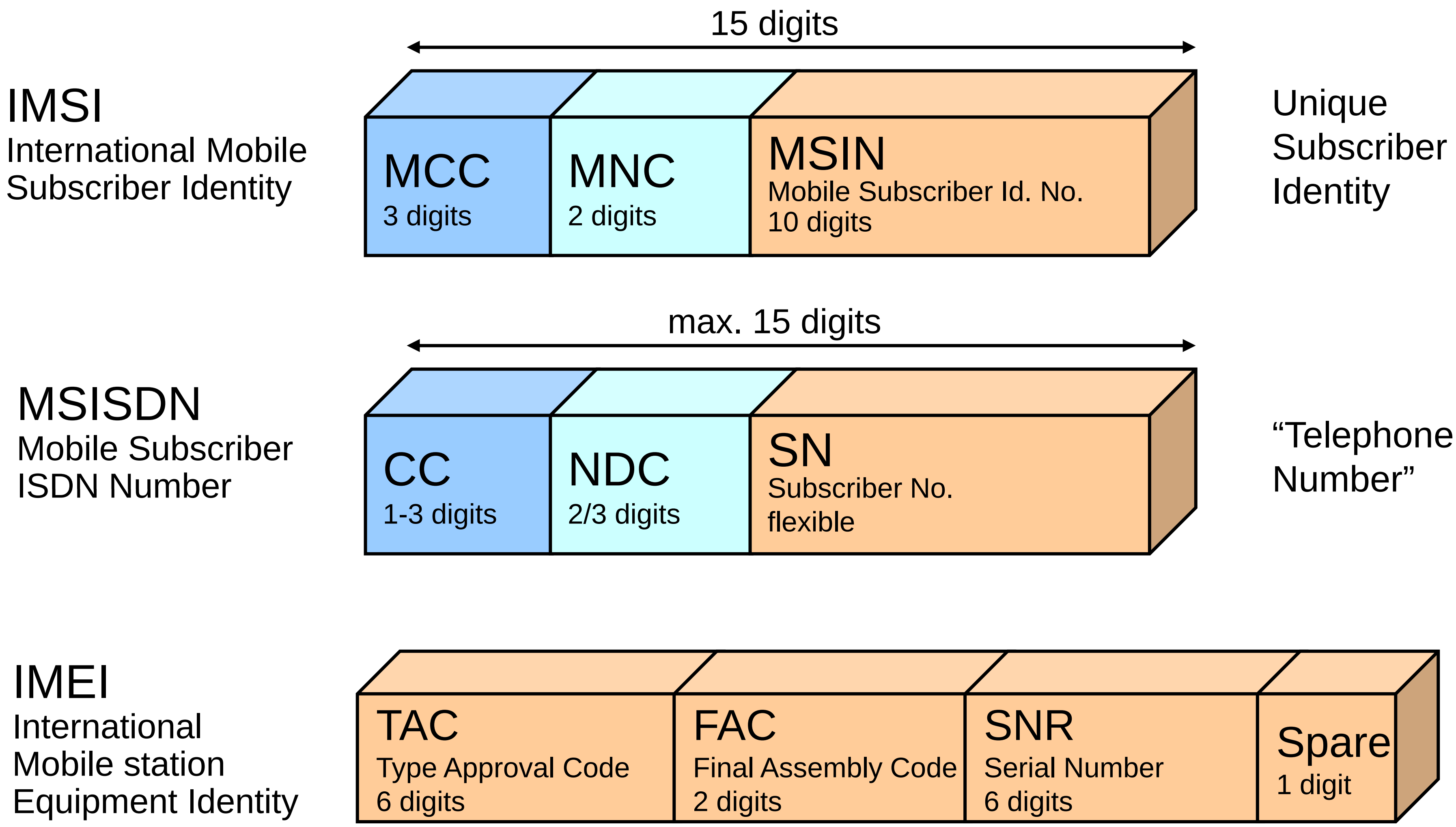
Connect two people (set-up and maintain the call)

Involved Tasks:
- Identify the called person.
- Determine his location.
- Route the call to him.
- Sustain the connection until conversation is over.
- Charge the caller.

The network keeps track of the subscriber through:

- Location update
- Help of various Identities & Data Bases

Mobile Networks Simplified
Subscriber Identity Numbers



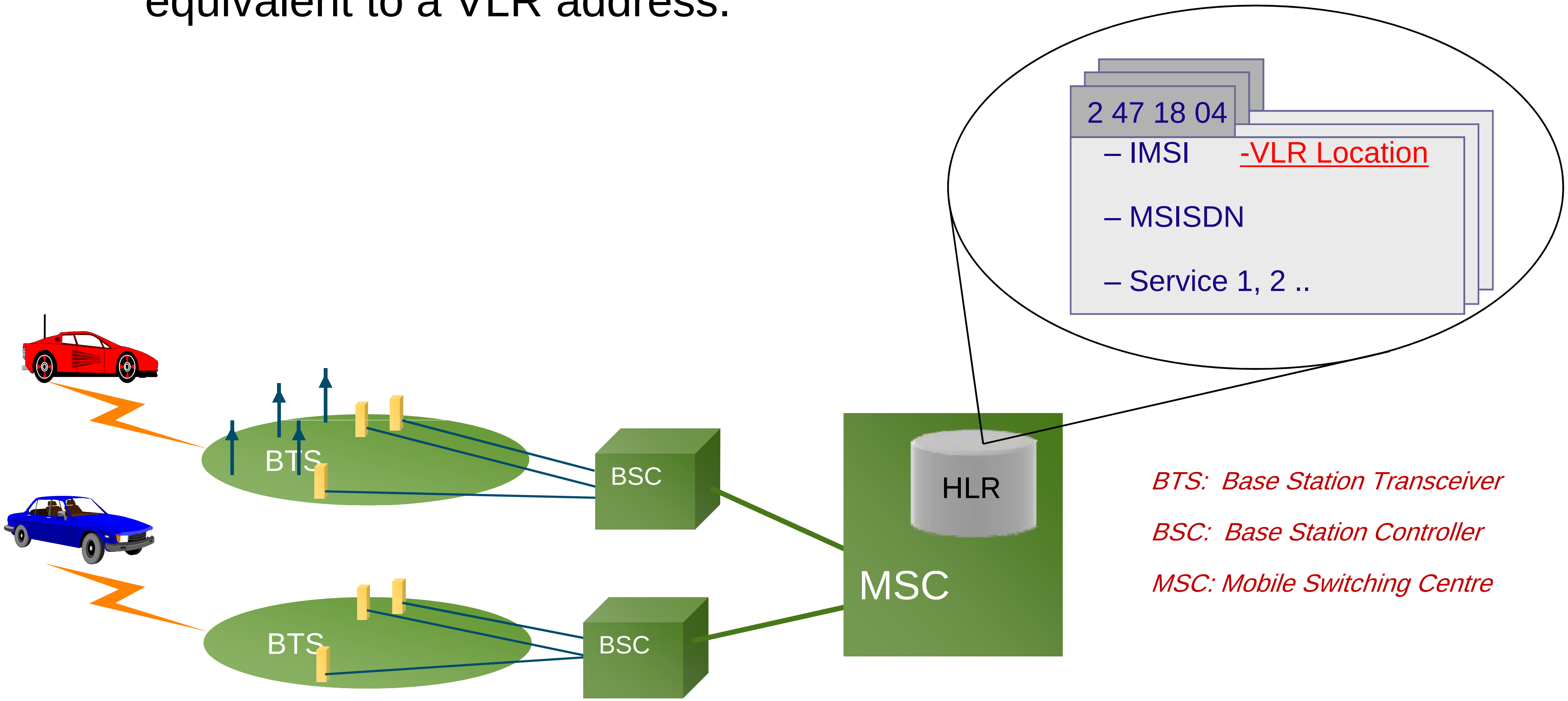
Mobile Networks Simplified
The First Database

- The Subscriber Identity Module (SIM)
  - a small memory device mounted on a card that contains user specific identification
  - The SIM includes:
    - Subscriber license
    - Personal identification (MSISDN, IMSI, PIN, PUK,...)
    - Subscriber key (Ki)
    - Algorithms (A3, A8)
    - Personal phone book
    - SIM toolkits,...

Subscriber Identity Module

Mobile Networks Simplified
The Second Database

- The Home Location Register (HLR)
  - Database which permanently keeps record of basic identification data of the subscribers including their current location (variable) equivalent to a VLR address.



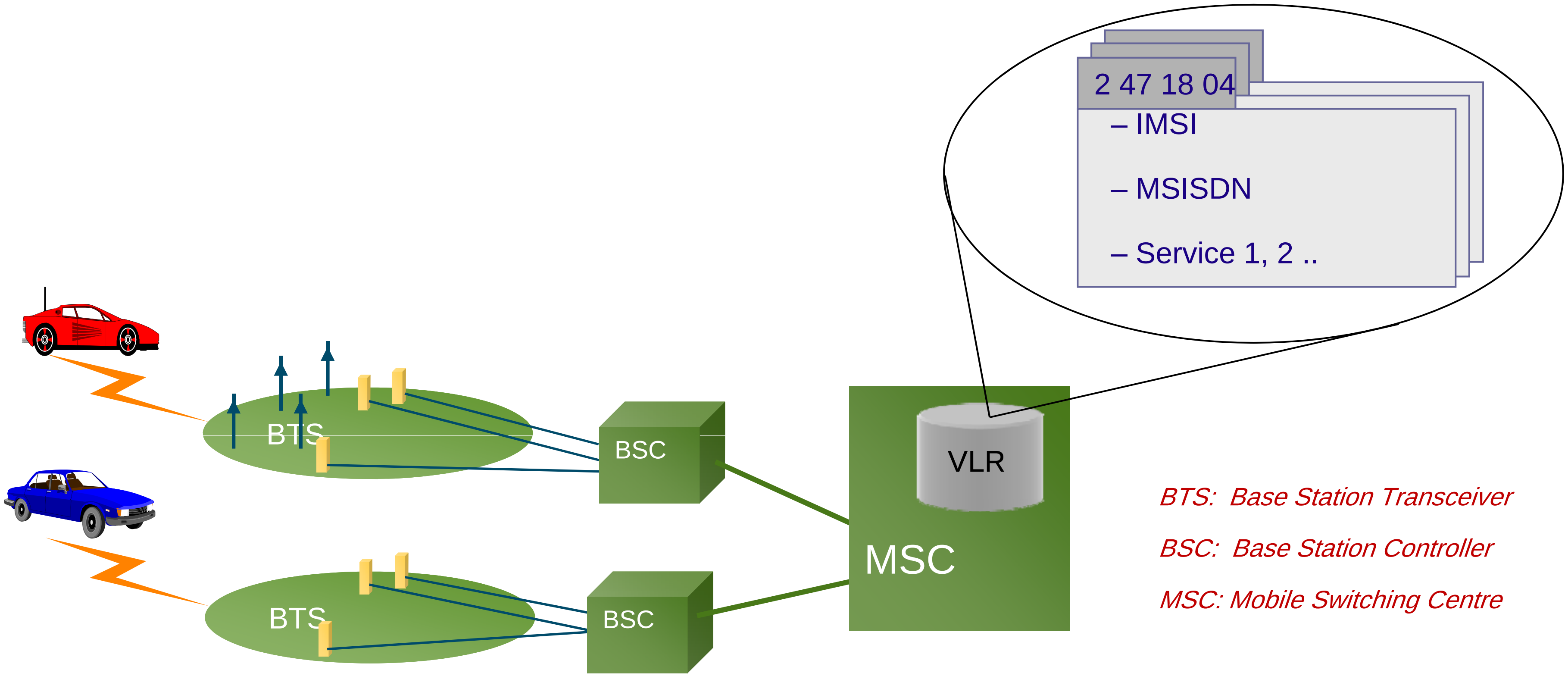
BTS: Base Station Transceiver

BSC: Base Station Controller

MSC: Mobile Switching Centre

Mobile Networks Simplified
The Second Database

- The Visitor Location Register (VLR)
  - Database which temporarily keeps record of subscribers currently located in the service area of the MSC.

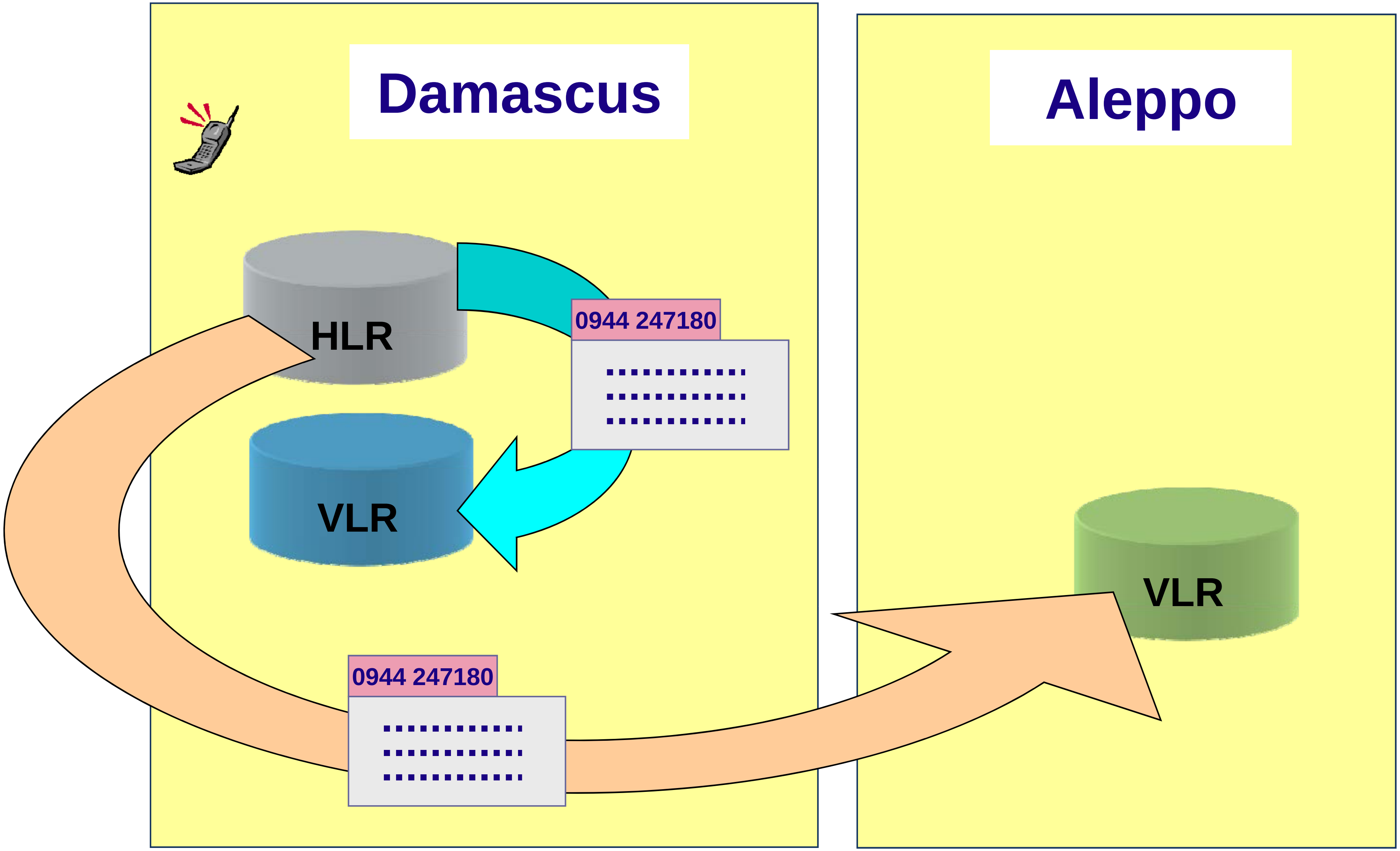


BTS: Base Station Transceiver

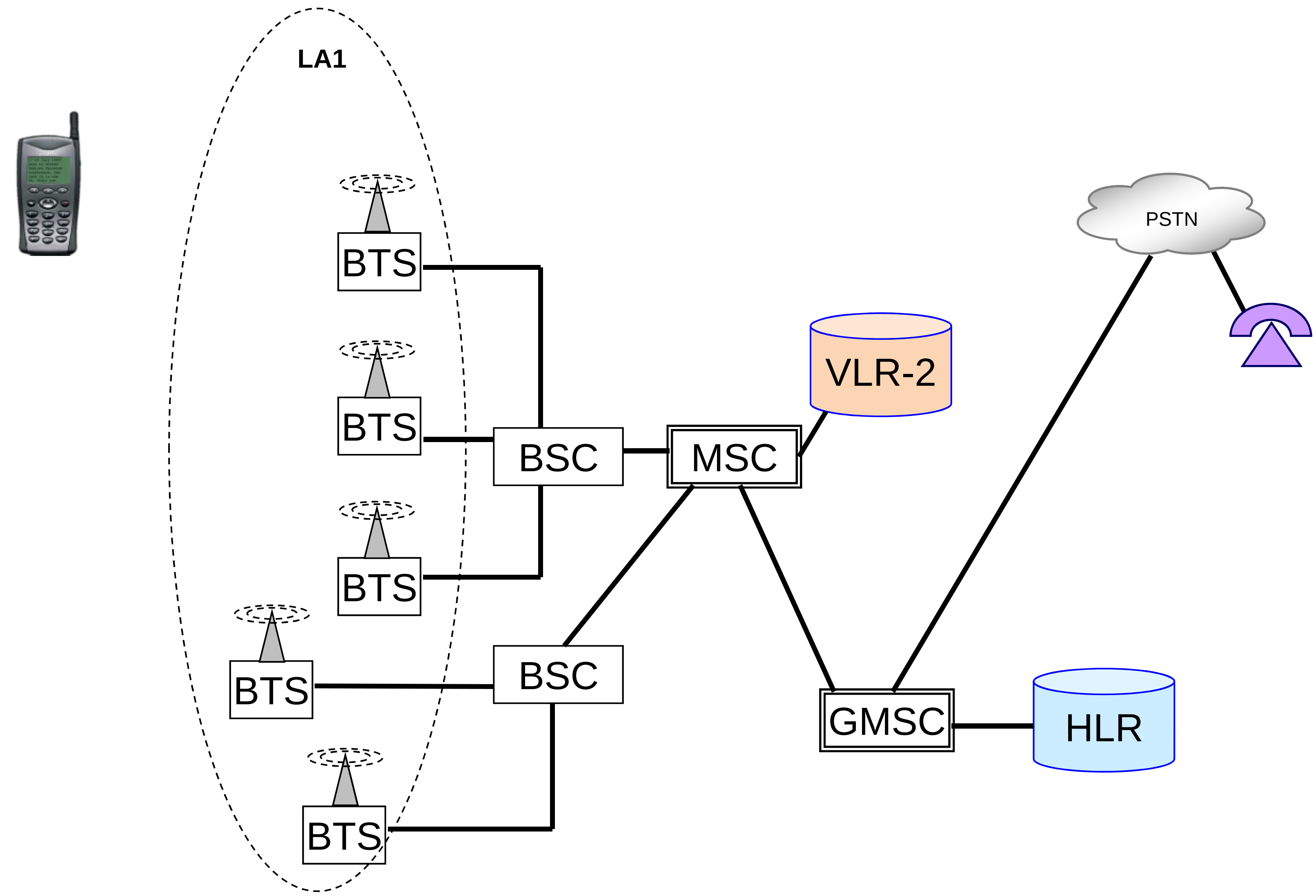
BSC: Base Station Controller

MSC: Mobile Switching Centre

Mobile Networks Simplified
Keeping Track of Subscriber's Data

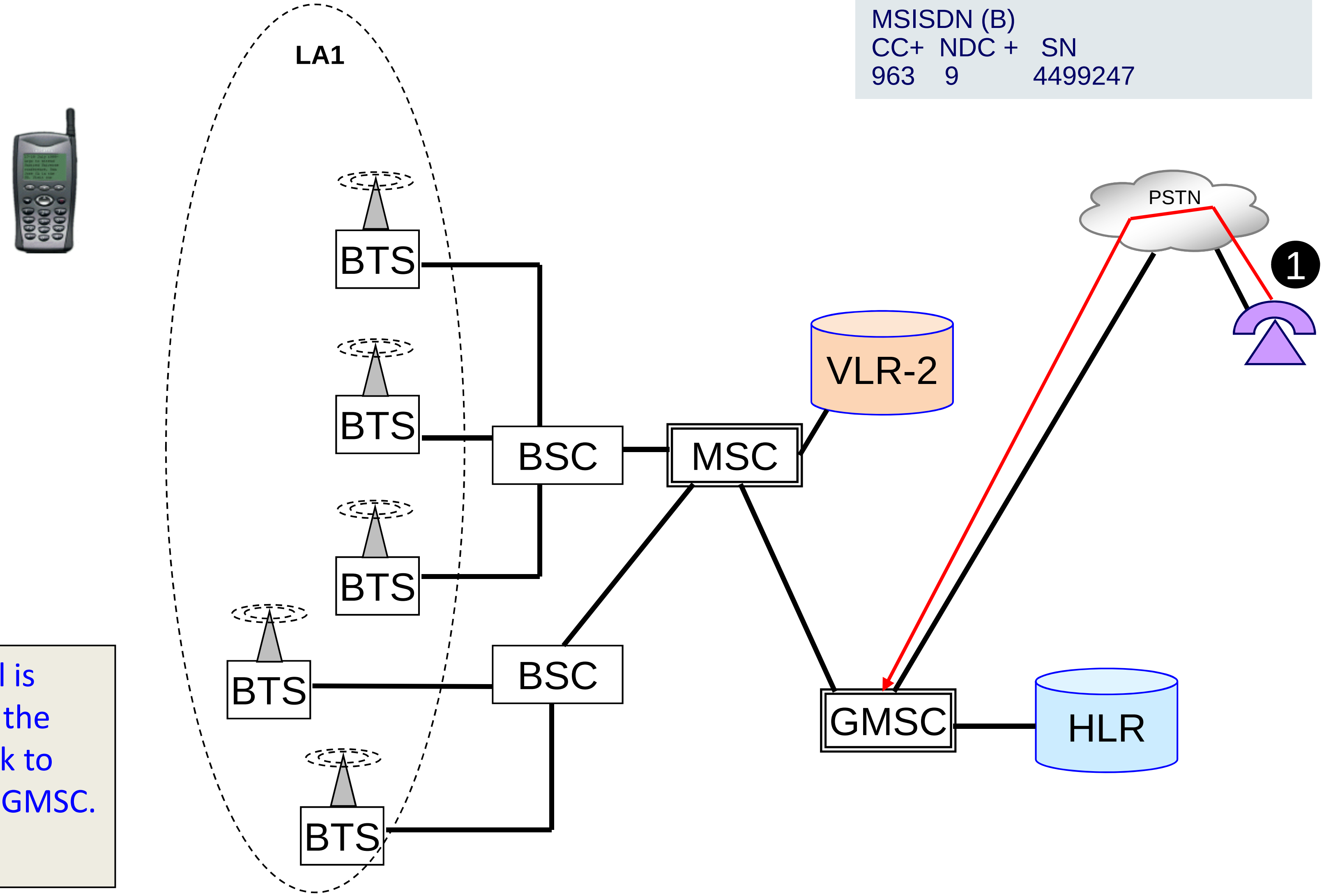


Mobile Networks Simplified
Example-Incoming Call



Mobile Networks Simplified
Example-Incoming Call

MSISDN (B)
CC+ NDC + SN
963 9 4499247



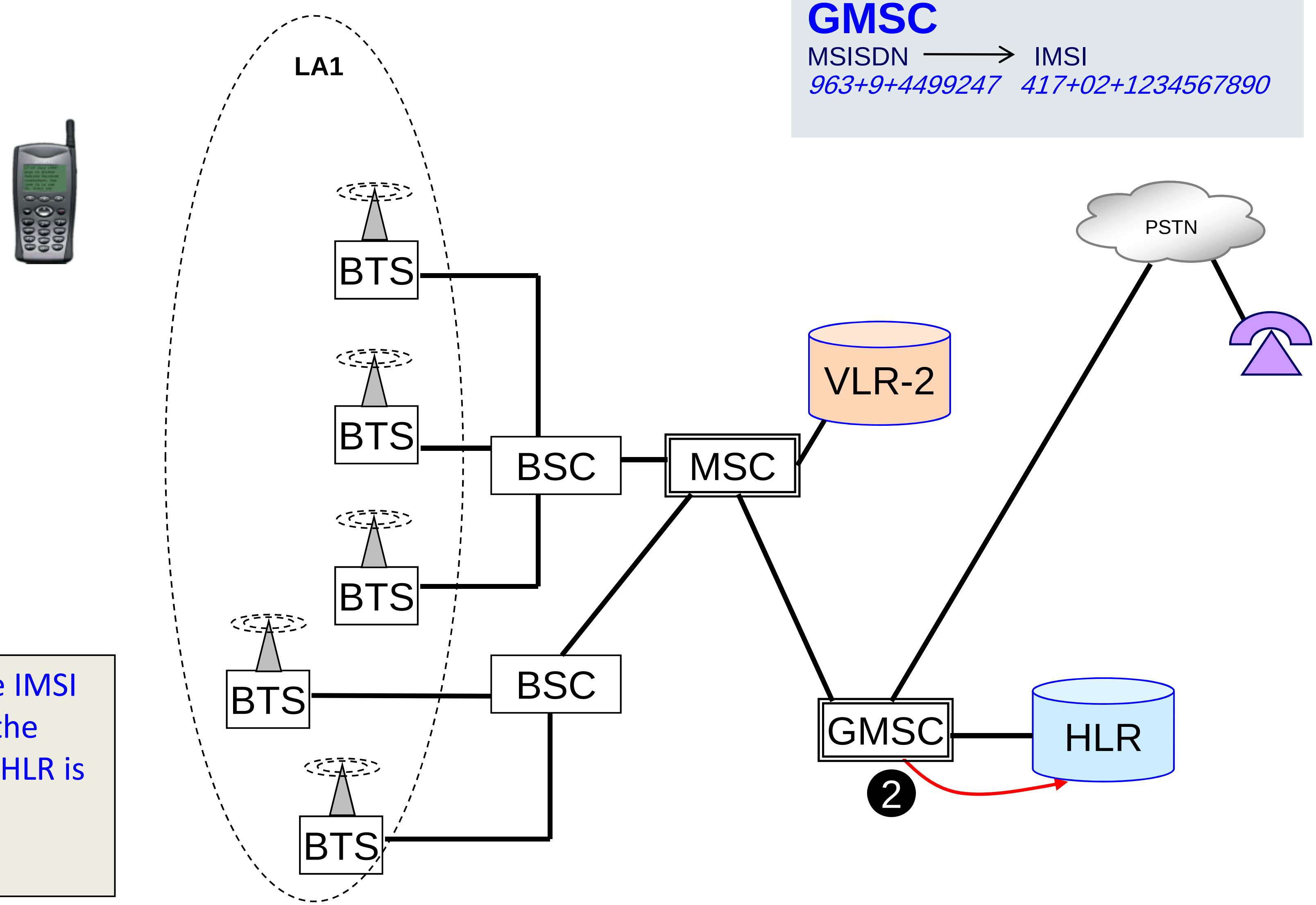
Incoming call is passed from the fixed network to the gateway GMSC.

Mobile Networks Simplified
Example-Incoming Call

GMSC

MSISDN → IMSI

963+9+4499247 *417+02+1234567890*

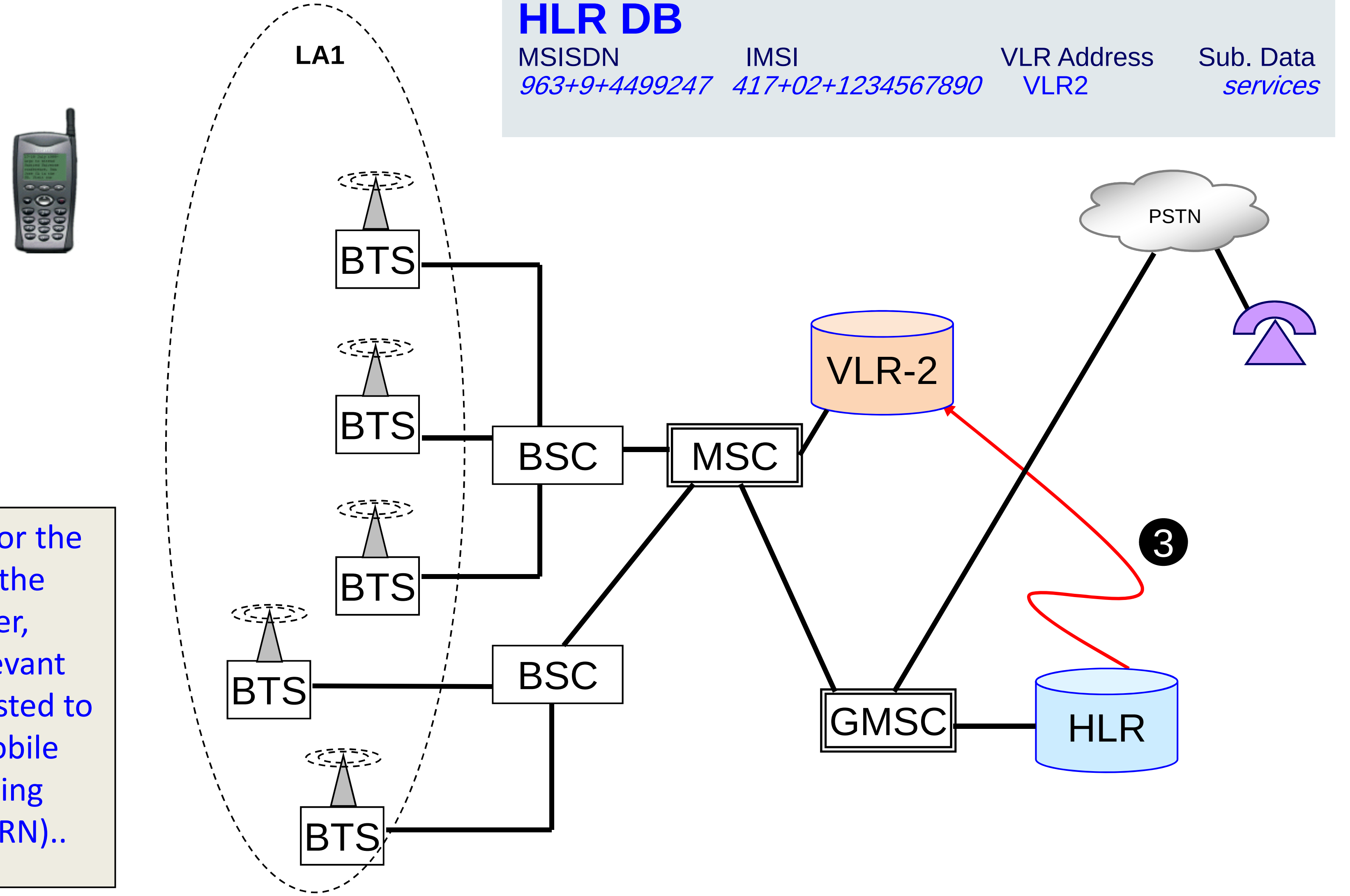


Based on the IMSI numbers of the called party, HLR is determined

Mobile Networks Simplified
Example-Incoming Call

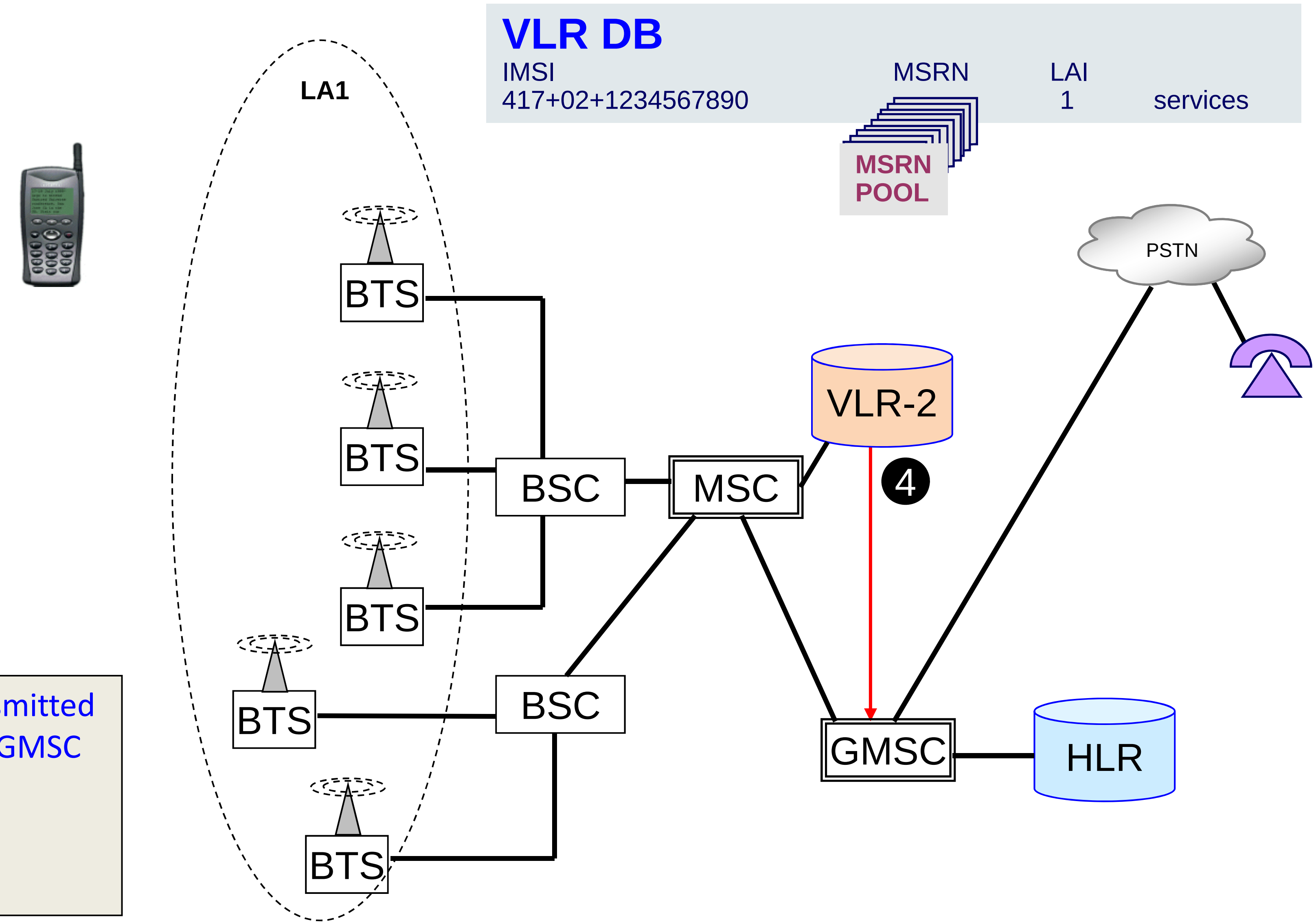
HLR DB

MSISDN	IMSI	VLR Address	Sub. Data
963+9+4499247	*417+02+1234567890*	VLR2	*services*



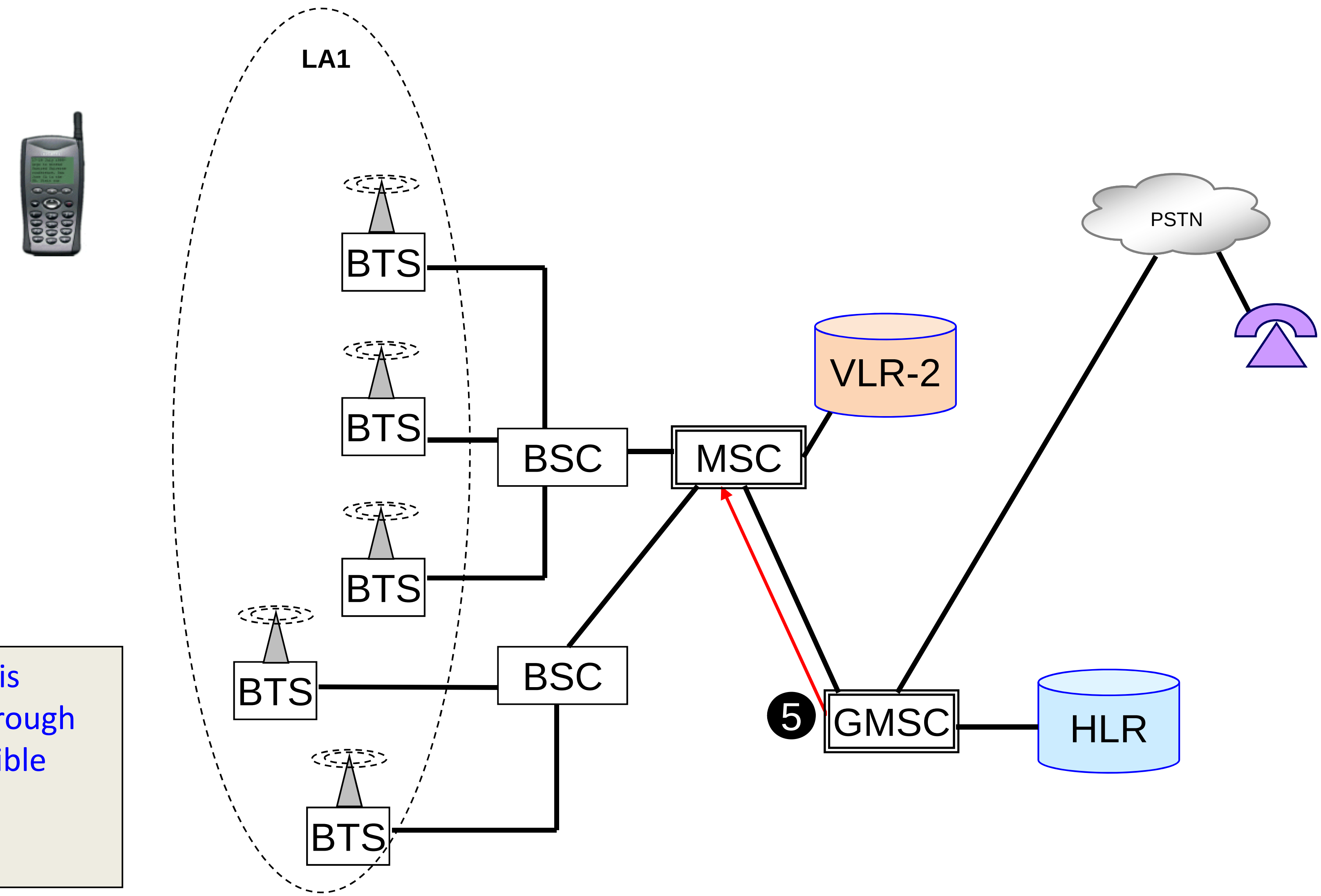
HLR checks for the existence of the called number, then the relevant VLR is requested to provide a mobile station roaming number (MSRN)..

Mobile Networks Simplified
Example-Incoming Call



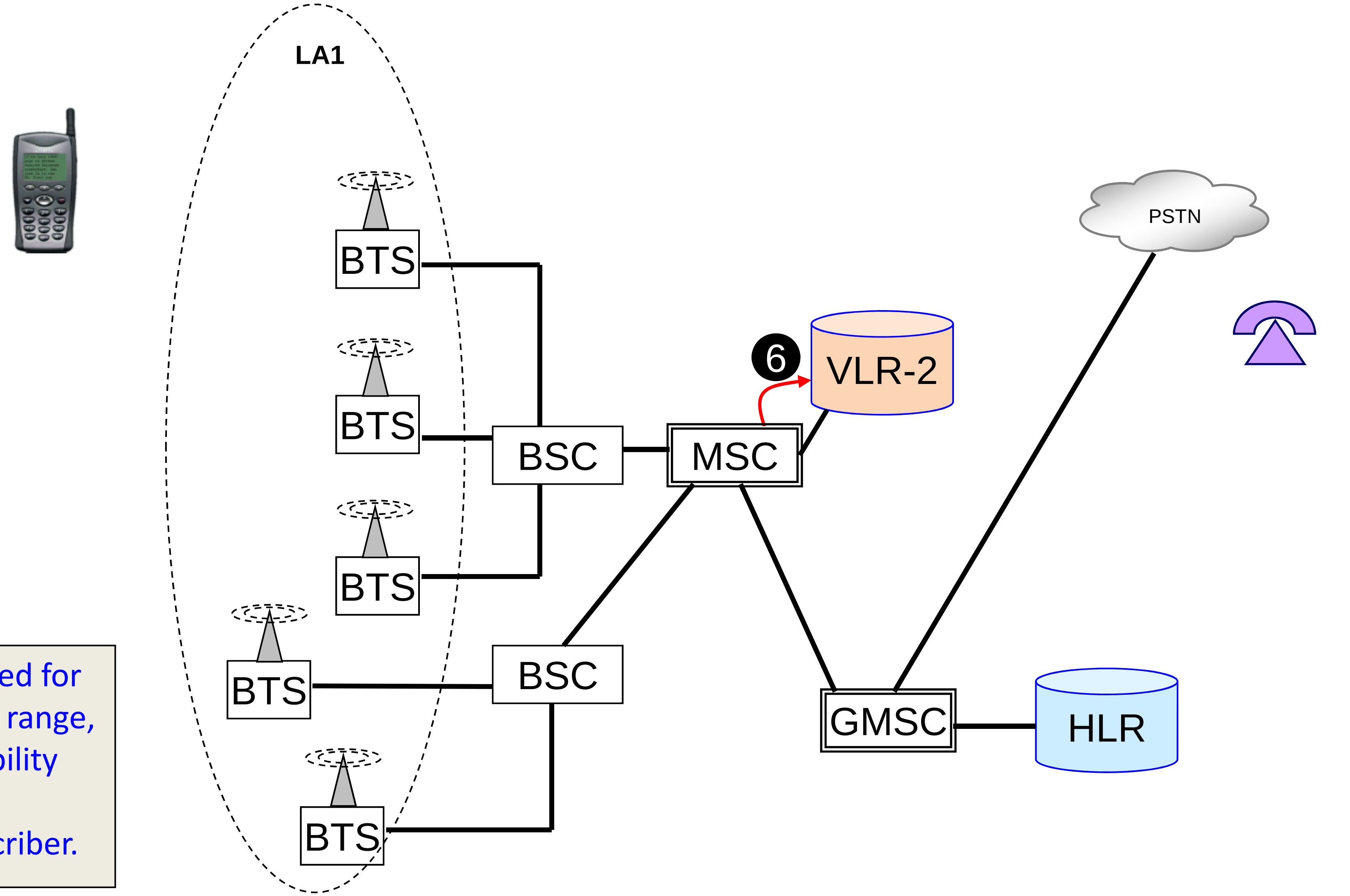
Replay transmitted back to the GMSC

Mobile Networks Simplified
Example-Incoming Call



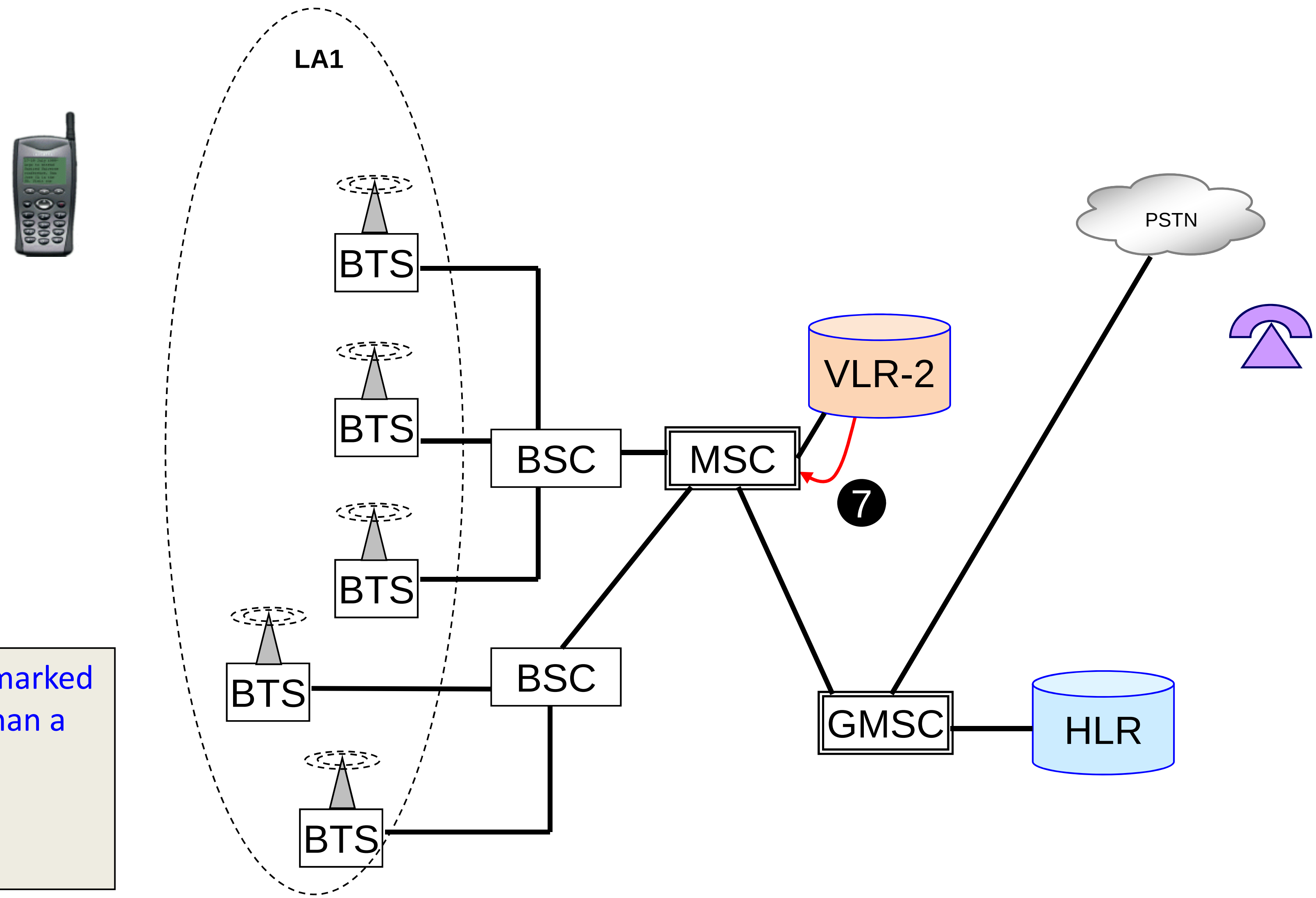
Connection is switched through the responsible MSC

Mobile Networks Simplified
Example-Incoming Call



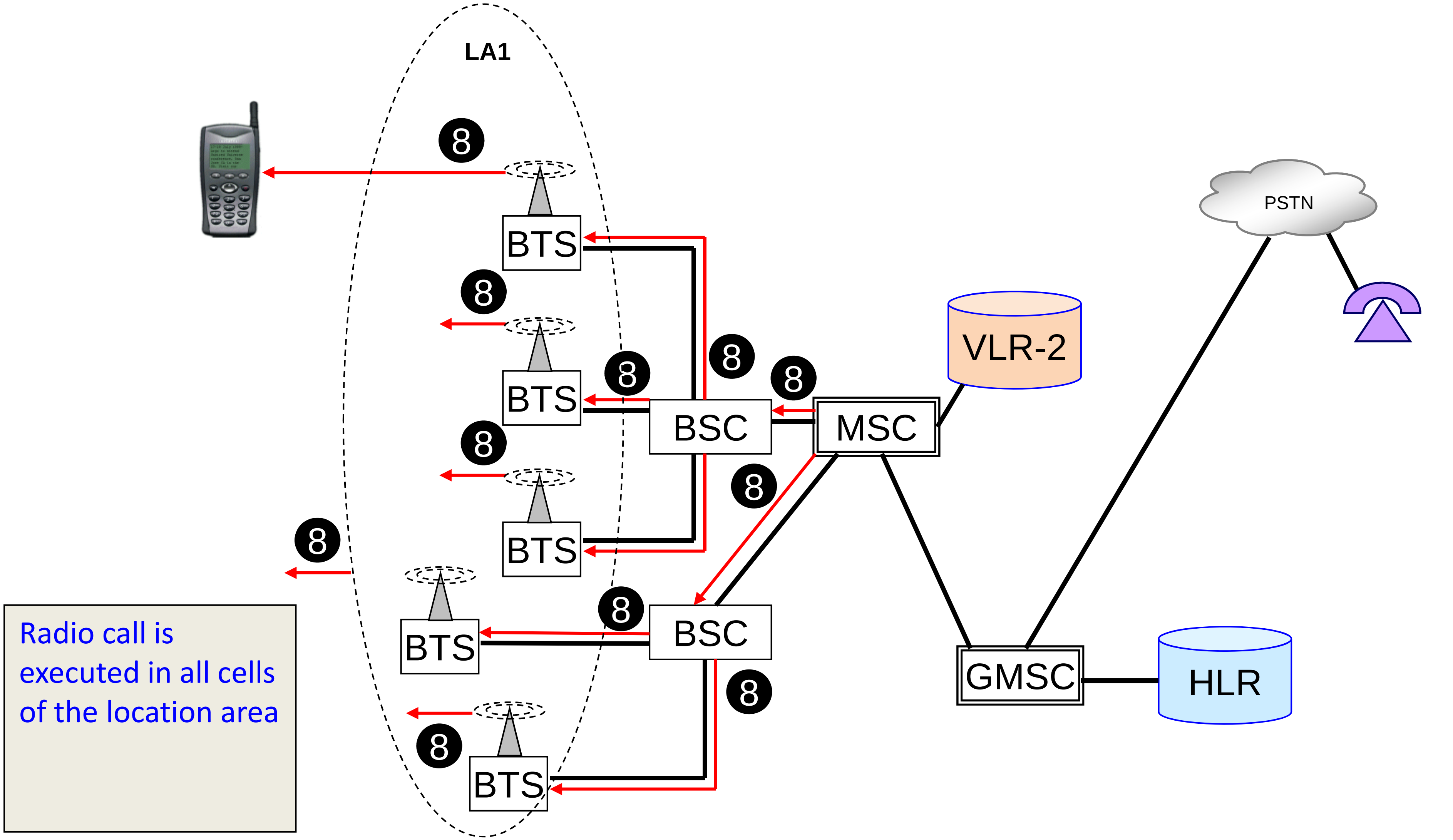
VLR is quarried for the location, range, and reach-ability status of the mobile subscriber.

Mobile Networks Simplified
Example-Incoming Call

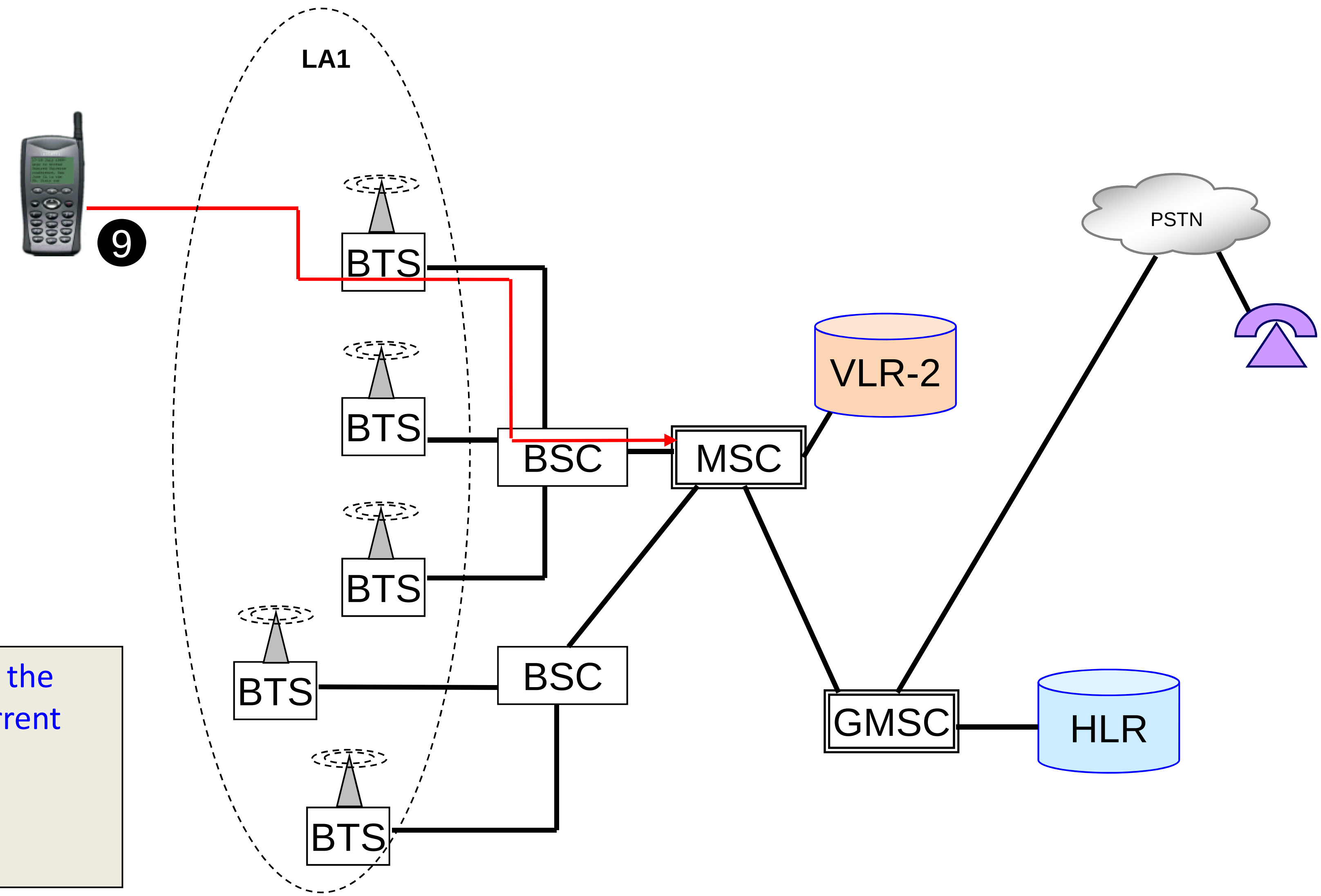


If the MS is marked reachable, than a radio call is enabled.

Mobile Networks Simplified
Example-Incoming Call

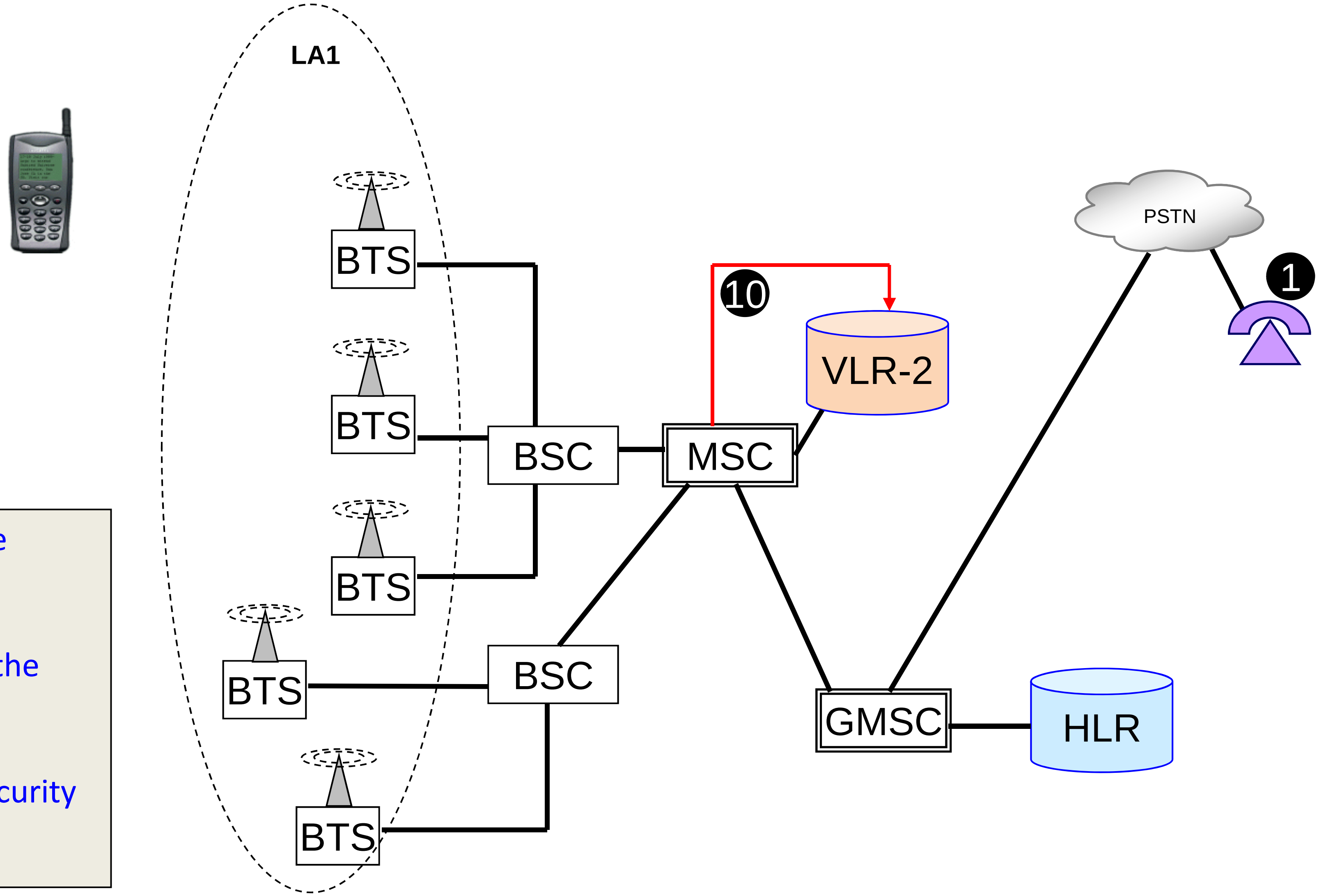


Mobile Networks Simplified
Example-Incoming Call



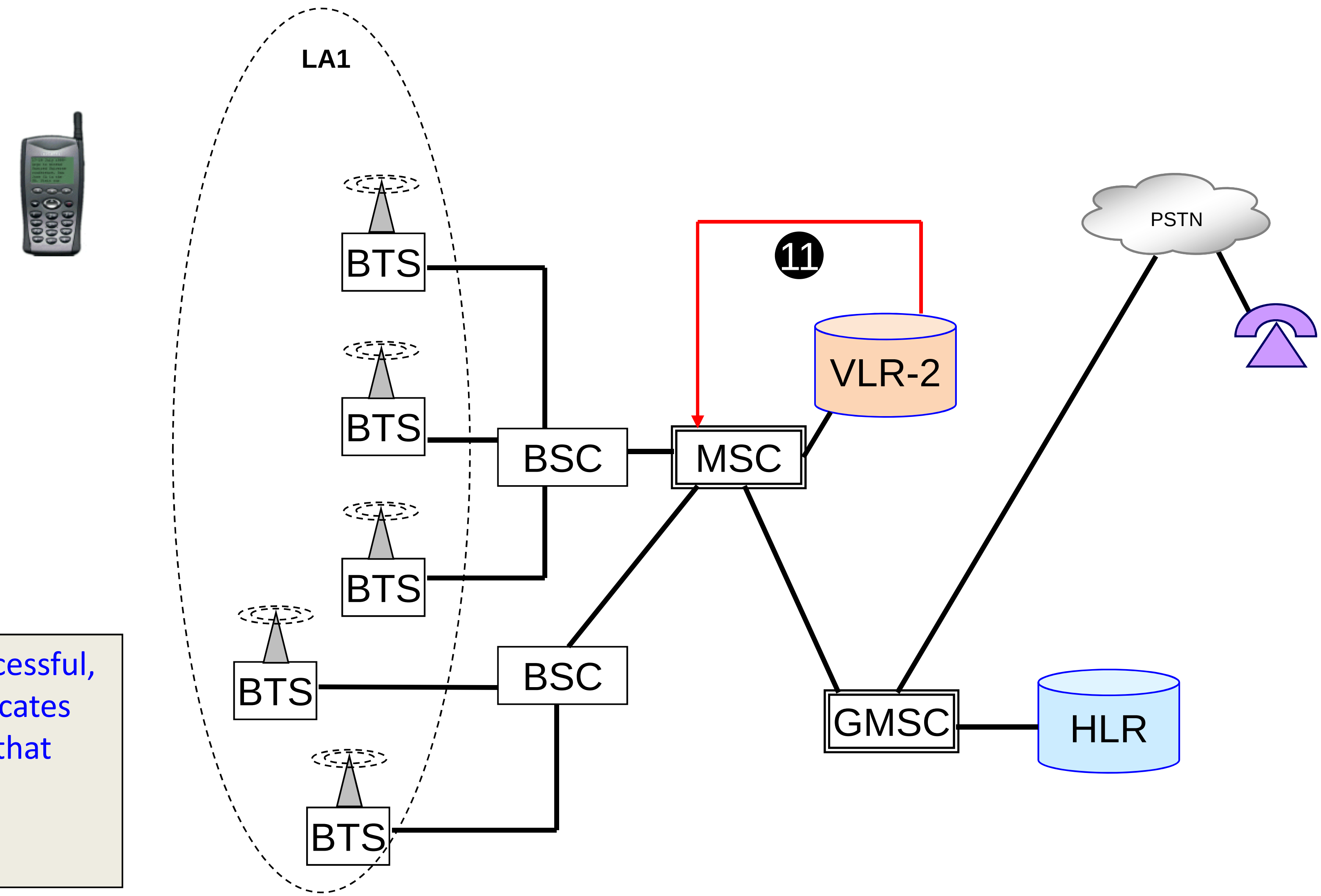
Replay from the MS in its current radio cell.

Mobile Networks Simplified
Example-Incoming Call



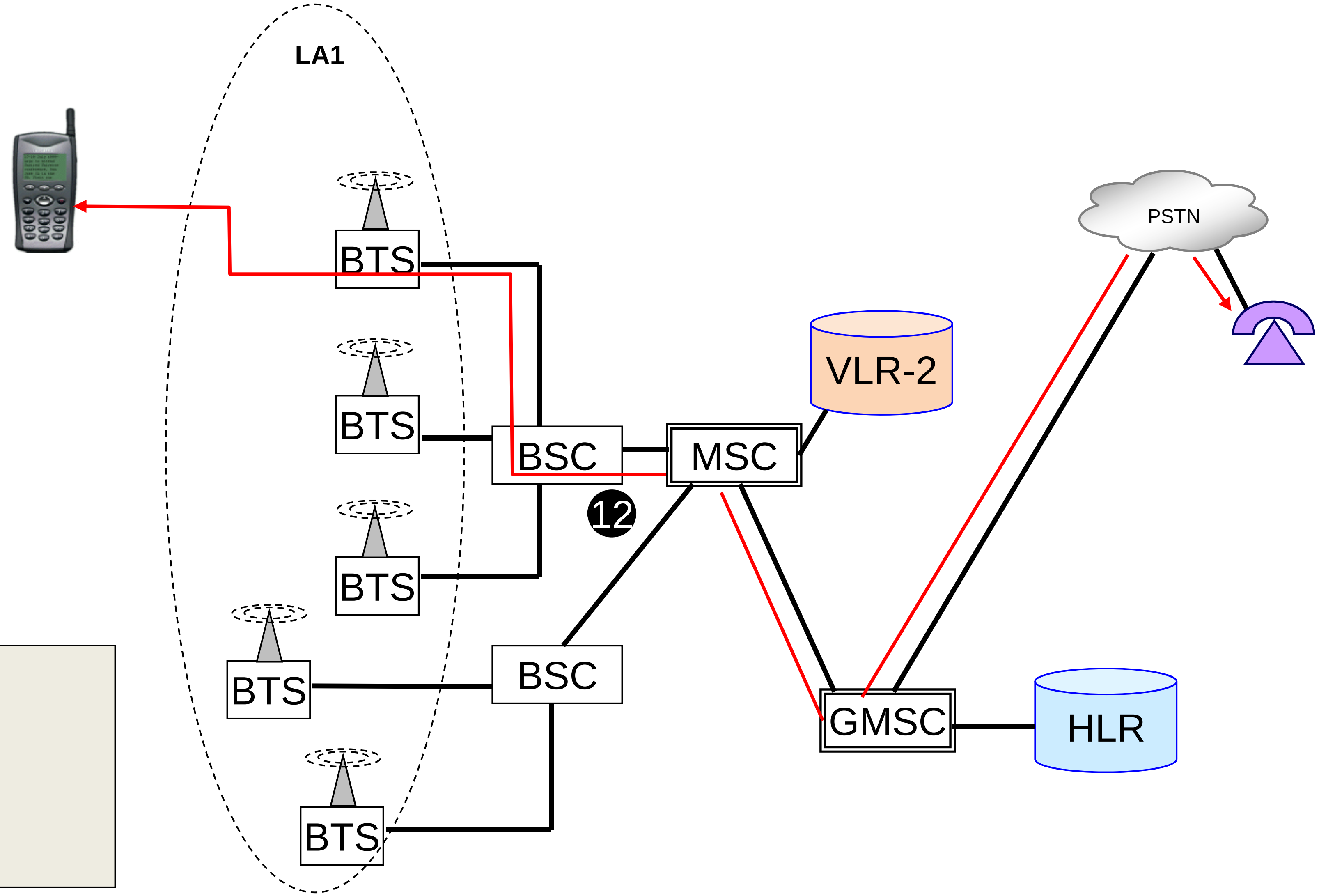
When mobile subscriber telephone responds to the page, then complete all necessary security procedures.

Mobile Networks Simplified
Example-Incoming Call



If this is successful, the VLR indicates to the MSC that call can be completed.

Mobile Networks Simplified
Example-Incoming Call

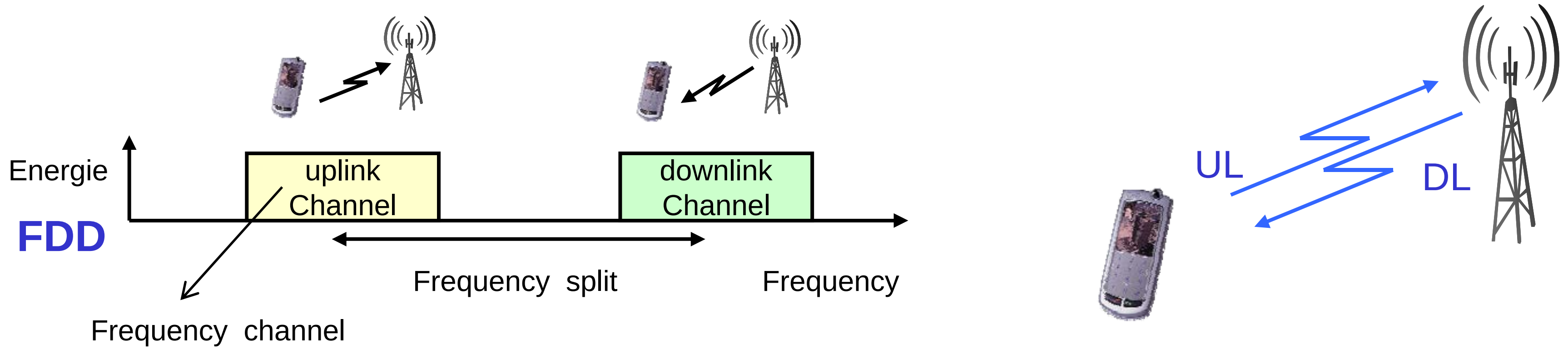


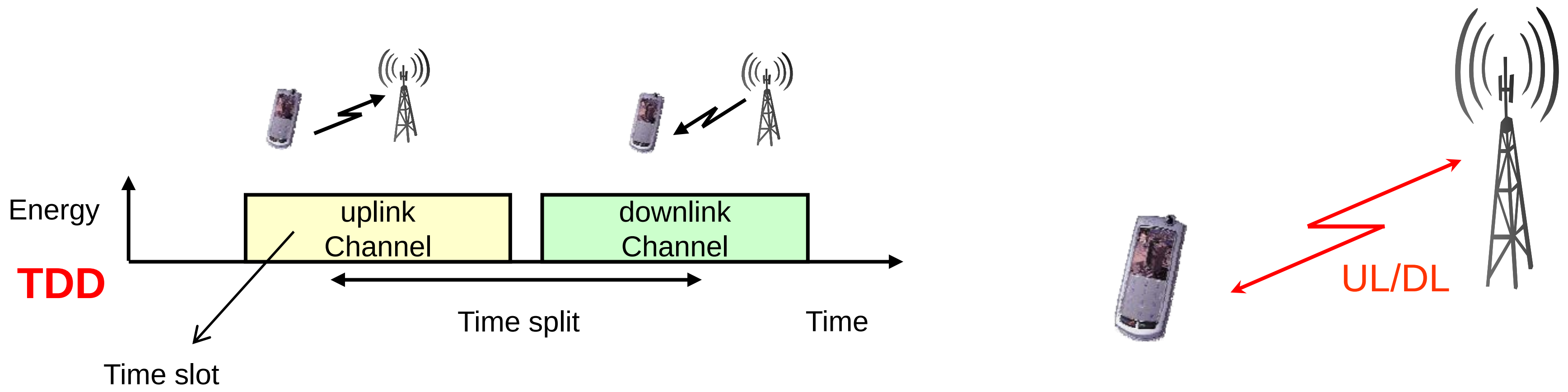
Call can be completed.

Mobile Networks Simplified
Type of Communication Channels

Type of Channel	Properties	Applications
Simplex	One-way only	FM radio, television
Half duplex	Two-way, only one at a time	Police radio
Full duplex	Two-way, both at the same time	Mobile systems

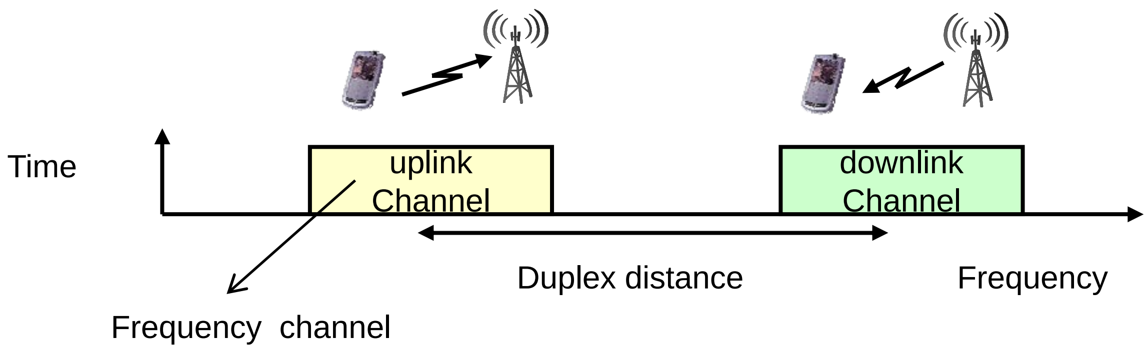
Mobile Networks Simplified
Duplexing Methods

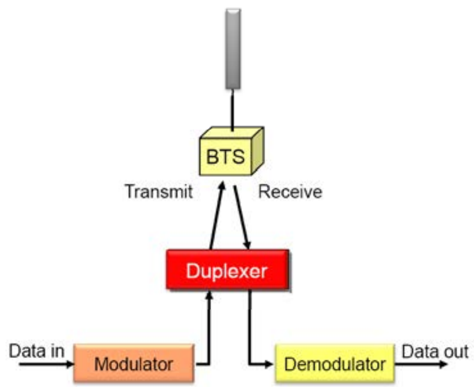




Duplexing
Frequency Division Duplex

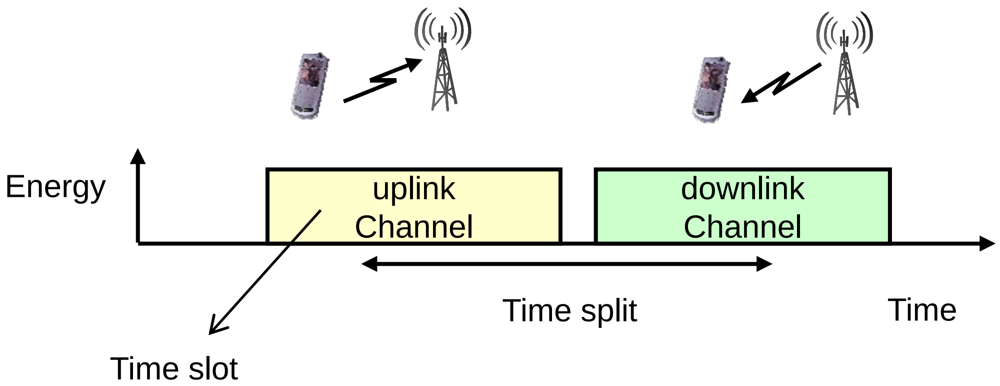
- Two simplex channels
- Forward/downlink channel (frequency band) for BS to mobile communication
- Reverse/uplink channel (frequency band) for mobile to BS communication
- Forward and reverse channels separated to keep interference between transmission and reception to a minimum
- Requires either 2 antennas or a duplexer to enable device to use both frequency channels with single antenna
- Because it requires less power to transmit a lower frequency over a given distance, uplink frequencies in mobile systems are always the lower band of frequencies – this saves valuable battery power of the MSs.

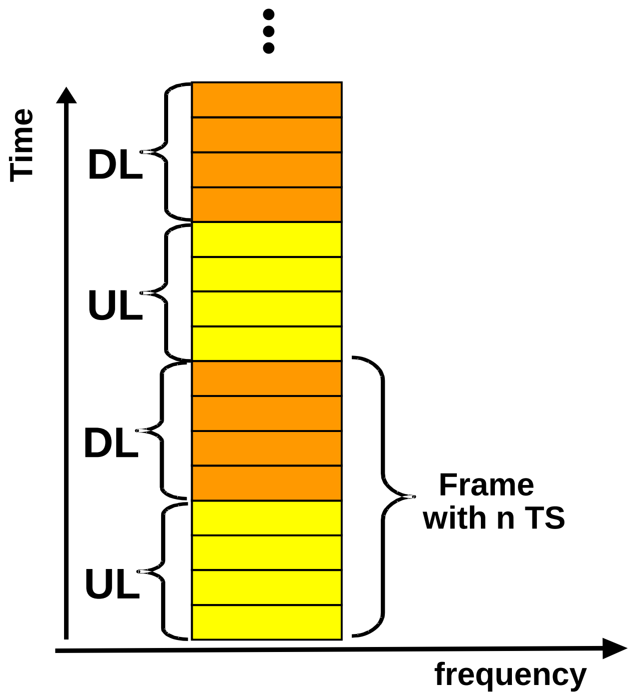




Duplexing
Time Division Duplex

1 “unpaired” frequency, shared for uplink and downlink





- Uses time instead of frequency to provide forward and reverse links
- Duplex channel consists of a forward and a reverse time slot
- If time separation between forward and reverse time slots is small, then transmission and reception of data appears simultaneous
- Due to the time latency created by TDD, it is not full duplex in the truest sense
- TDD allows communication on a single channel and makes a duplexer superfluous

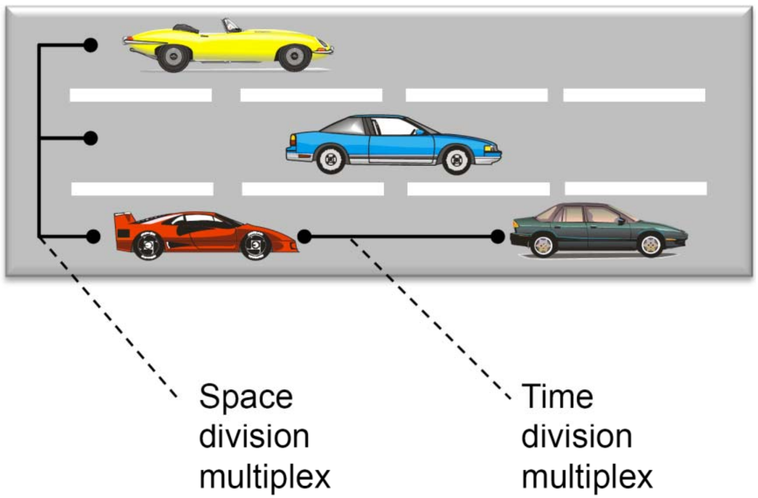
Multiplexing & Medium Access
Basics

Motivation

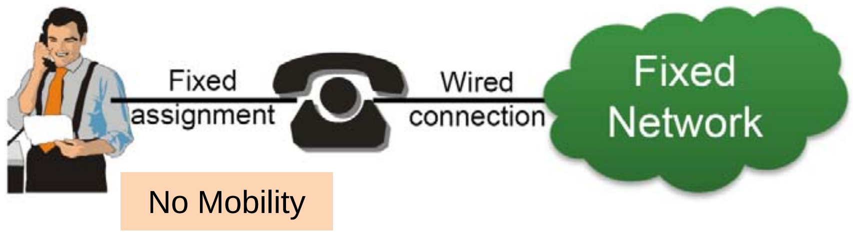
- Task of multiplexing is to assign space, time, frequency, and code to each communication channel with a minimum of interference and a maximum of medium utilization
- Communication channel refers to an association of sender(s) and receiver(s) that want to exchange data
- Classification of multiplexing
  - Four dimensions:
    - Space
    - Time
    - Frequency
    - code

Analogy

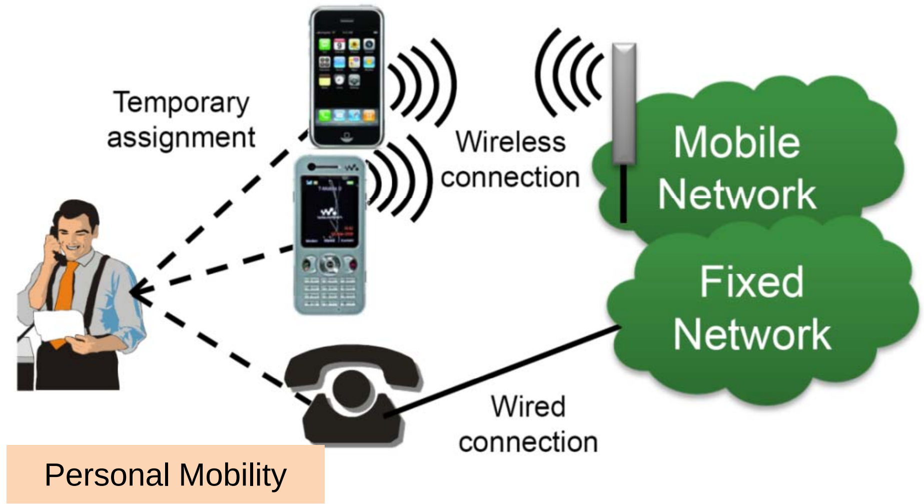
- Highways with several lanes
  - many users: car drivers
  - medium: highway
  - interference: accidents



Mobility Classification
Terminal & Personal Mobility

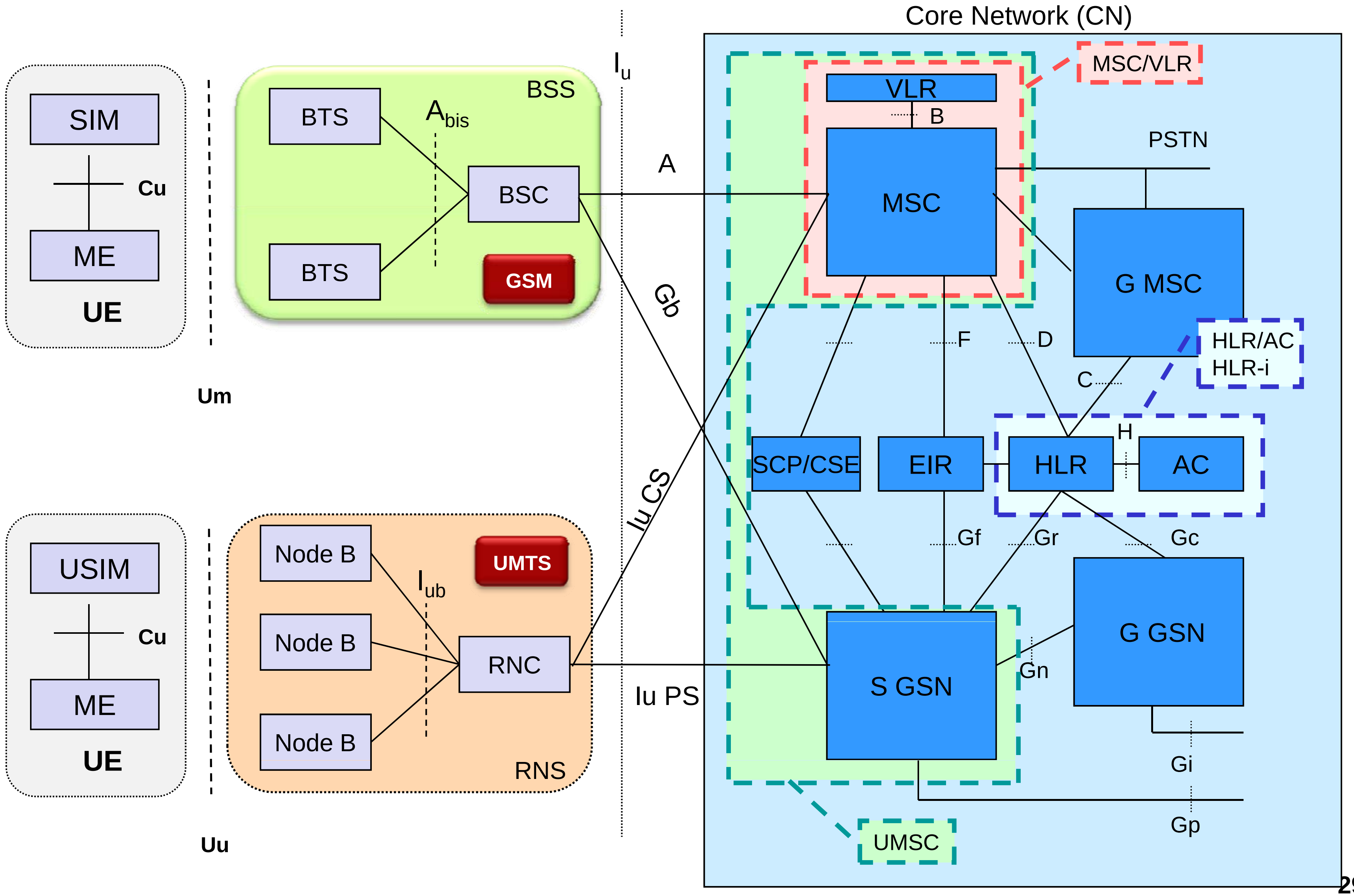


- Wireless connection between terminal/device and network access point.
- Maintains registration/call/connection between terminal and network while in motion.

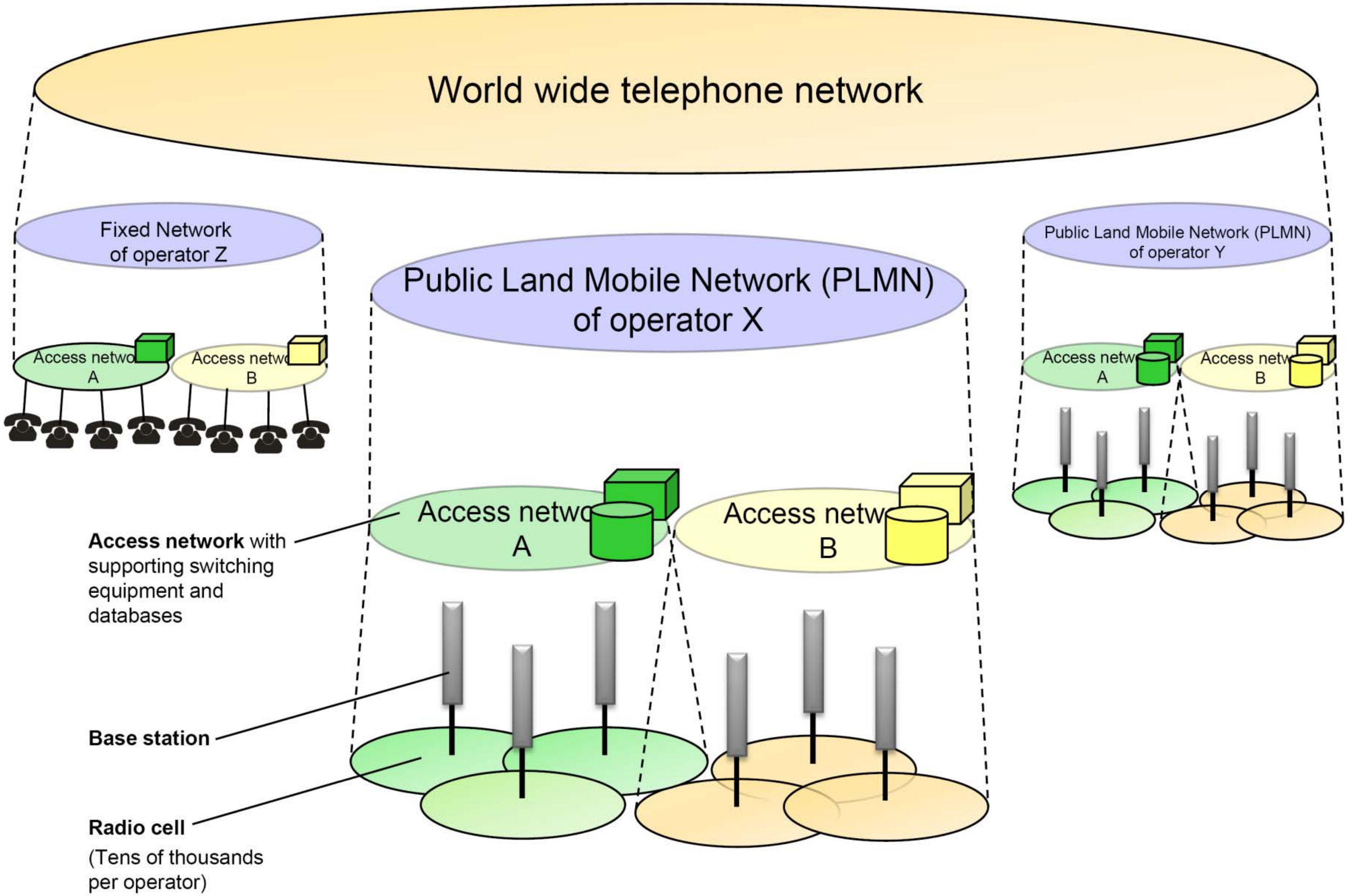


- Enables subscriber to be reachable regardless of terminal, terminal type, operator/provider domain, and type of network.
- User profiles are available across terminal/network/operator boundaries.
- Features: Call forwarding, Roaming, Number portability.

Mobility Classification
Network Structure



Mobility Classification
Mobile Network Topology



Mobility Classification
Micro, Macro, and Global Mobility

High

Location update frequency

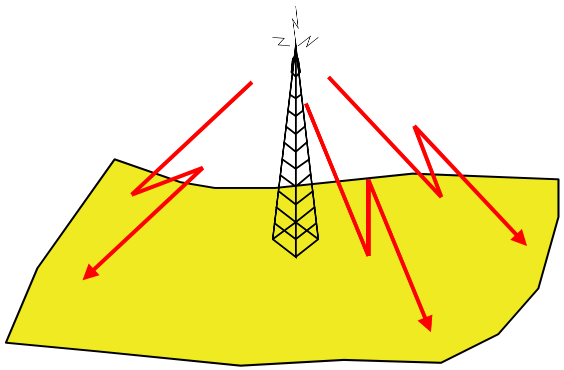
- Micro Mobility
  - Mobility support within a radio cell or between different cells, but within a single access network
  - Mobility management at layer 2 (Data Link Layer)
- Macro Mobility (Intra-domain Mobility)
  - Mobility support between the different access networks of a PLMN or within a certain geographic region
  - Mobility management at layer 3 (Network Layer)
- Global Mobility (Inter-domain Mobility)
  - Mobility support between different PLMNs
  - Mobility management at layer 3 and/or above

Distance

Far

Motivation
Why the Cellular Concept? (I)

- **Scenario 1:** provide mobile services by a single high-power transmitter/receiver mounted on a tall tower
- Example
  - Providing a city with a radio communication service
  - Total bandwidth available is *25 MHz*
  - Each user requires *30 KHz* of bandwidth for voice communication
  - If one antenna is used to cover the entire town, *25 MHz/30 KHz=833* simultaneous users can be supported



- **High power transmitter**
- **Large coverage area**

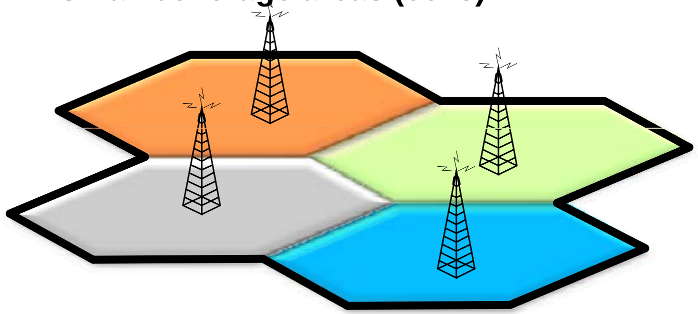
➔ **System capacity can only be increased by increasing the total bandwidth of the system**
➔ **Any attempt to reuse the same frequency channels throughout the system would result in interference**
➔ **High power consumption at the mobile device**

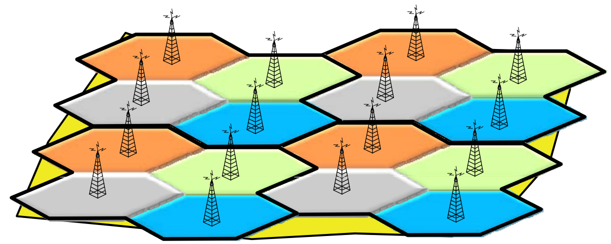
Motivation

Why the Cellular Concept? (II)

- **Scenario 2:** replace the single, high-power transmitter with many low-power transmitters, each providing coverage to only a small portion of the service area.
- Each base station is allocated a portion of the total bandwidth.
- Example
  - Divide total bandwidth of *25 MHz* into four sets and assign one set to each base station.
  - Each cell has a spectrum of *25MHz/4=6.25 MHz* allocated to it.
  - Number of simultaneous users per cell is *6.25 MHz/30 KHz=208.*
  - Number of simultaneous users per cluster is *4x208=832.*
  - If the coverage area of the entire system is divided into four clusters, the total number of simultaneous users is *832x4=3328.*

- **Low power transmitters**
- **Small coverage areas (cells)**





Motivation
Fundamental Idea of the Cellular Concept

- **Frequency reuse**
  - Utilizes the path loss of electromagnetic waves.
  - Same group of radio 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.
  - Available spectrum is spatially reused so that the same spectrum can simultaneously support multiple users separated from one another by a certain distance.

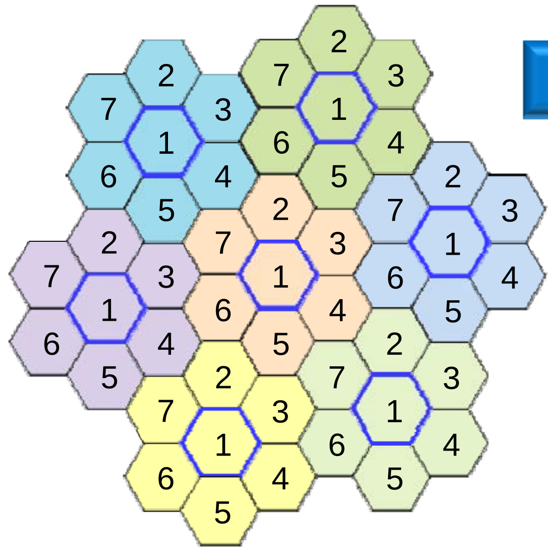
- **Radio channel allocation**
  - Base stations of adjacent cells are assigned different groups of radio channels so that all
    - available channels are assigned to a relatively small number of neighboring base stations,
    - interferences between base stations using the same group of radio channels (and the mobile users under their control) are minimized,
  - Available channel groups are distributed throughout a system's geographic region and may be reused as many times as necessary.

As more capacity is needed within a particular mobile system, the number of base stations can be increased (along with a corresponding decrease in transmitter power to avoid interference), thereby <u>providing additional radio capacity with no additional increase in radio spectrum</u>.

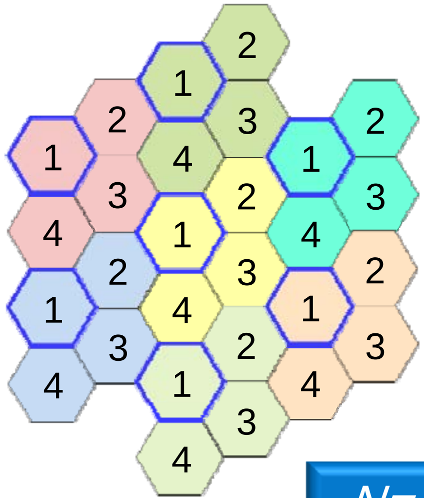
Cellular Concept
Formation of Clusters

- Clustering of cells: regular repetition of frequencies.
- A **cluster** contains all the frequencies of the mobile radio system.
- Size of a cluster is characterized by the number of cells per cluster N *(which determines the frequency reuse distance D).*
- No frequency can be reused within a cluster.
- The frequencies of a set f_i *may be reused at the earliest in the neighboring cluster*
- The larger a cluster
  - the larger the frequency reuse distance
  - the larger the signal-to-noise ratio
  - the smaller the number of channels and number of active subscribers per cell
- Number of cells N *per cluster is given by*

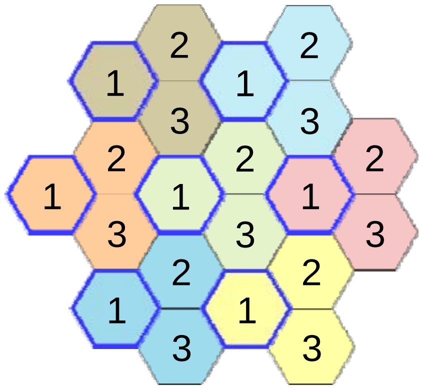
$$N = i^2 + ij + j^2 \quad i, j \in \mathrm{N}^+$$



N=7



N=4



N=3

Motivation
Pros and Cons of Cellular Systems

- **Advantages**
  - **Higher capacity**
    - If one transmitter is far from another, i.e., outside the interference range, it can reuse the same frequencies
    - Decreasing cell size allows to serve more users per km2
  - **Less transmission power**
    - Receiver far away from a base station would need much more transmit power (problematic for mobile devices)
  - **Local interference only**
    - Long distances between sender and receiver result in even more interference problems
  - **Robustness**
    - If one antenna fails, this defect only influences communication within a small area

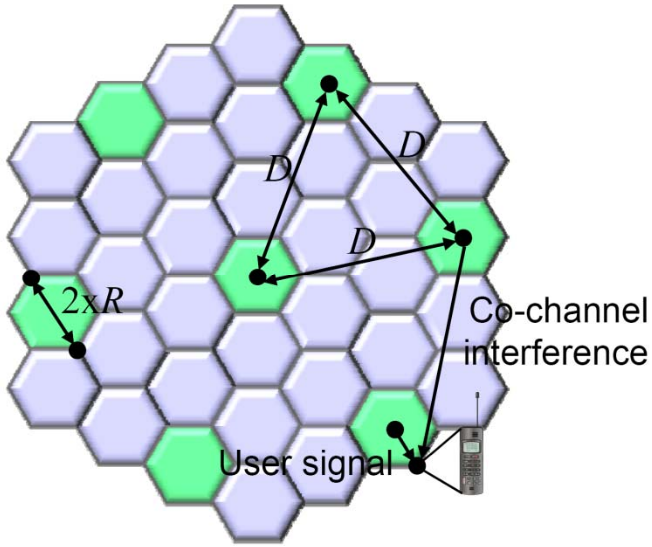
- **Disadvantages**
  - **Infrastructure needed**
    - Complex infrastructure needed to connect all base stations
    - Including many antennas, switches for call forwarding, location registers to find a mobile station etc.
  - **Handover needed**
    - Changing from one cell to another with an ongoing connection, a handover must be performed
    - Can happen quite often (depending on the cell size and the speed of movement)
  - **Frequency planning**
    - Careful distribution of frequencies to avoid interferences between transmitters

Cellular Concept

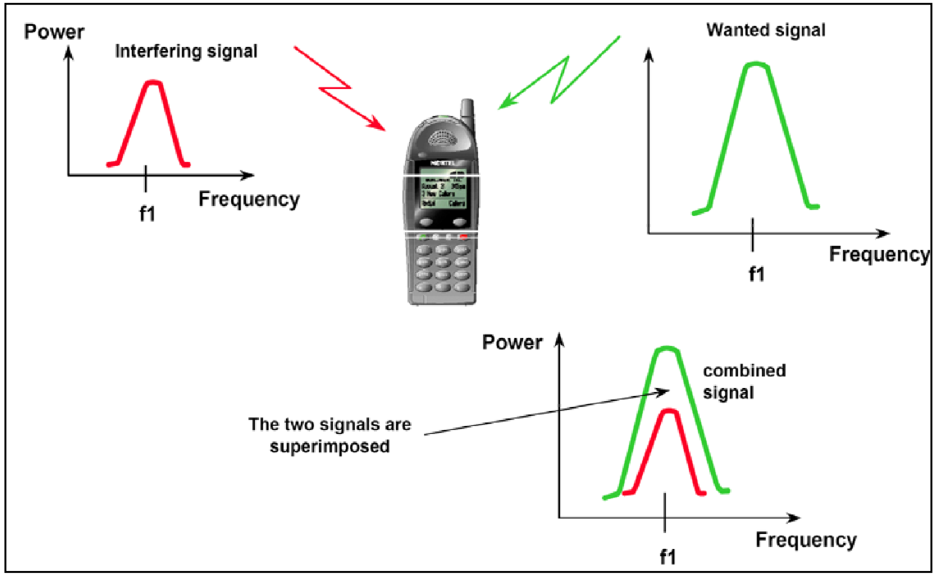
Co-channel cells and Frequency Reuse Distance

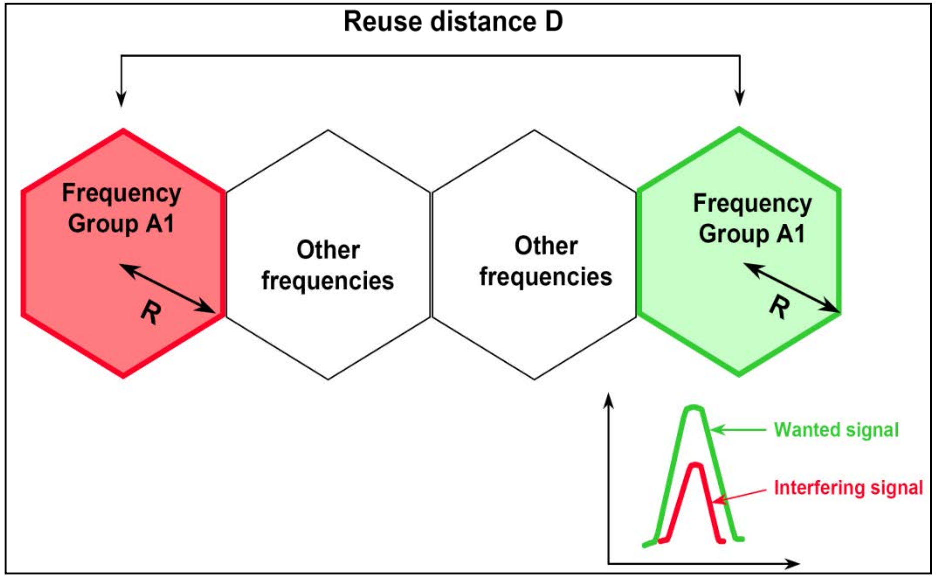
- Channel allocation
  - To each cell i a subset of frequencies f_i is assigned from the total subset assigned to the respective mobile network.
- Co-channel cells
  - Cells that have been assigned the same channel allocation (i.e., the same set of frequencies) in a given mobile network.
- Co-channel interference
  - Interference between signals from co-channel cells
  - To reduce co-channel interference, co-channel cells must be physically separated by a minimum distance (exception: systems based on CDMA).

- Frequency reuse distance D
  - Cells with distance D to cell i are assigned one or all of the frequencies from the set f_i belonging to cell i.
  - If D is chosen efficiently large, the co-channel interference remains small enough to not affect speech quality.



Cellular Concept
Co-channel cells and Frequency Reuse Distance

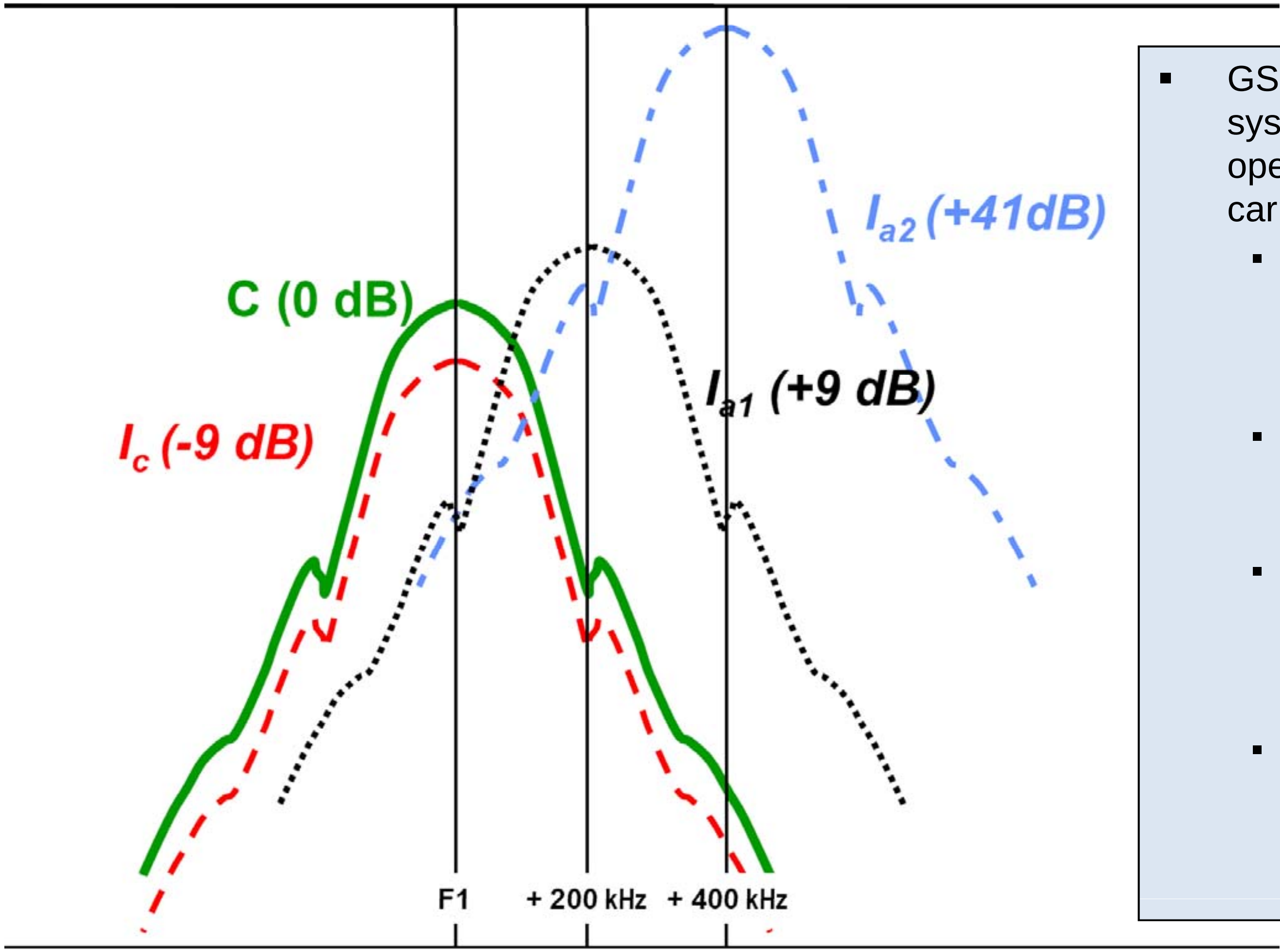




Co-channel interference occurs when two signals are being transmitted by two different cells on the same frequency and both are received by the same telephone mobile.
The two signals are then superimposed, interfering with one another and creating a signal that cannot be recognized.

Cellular Concept

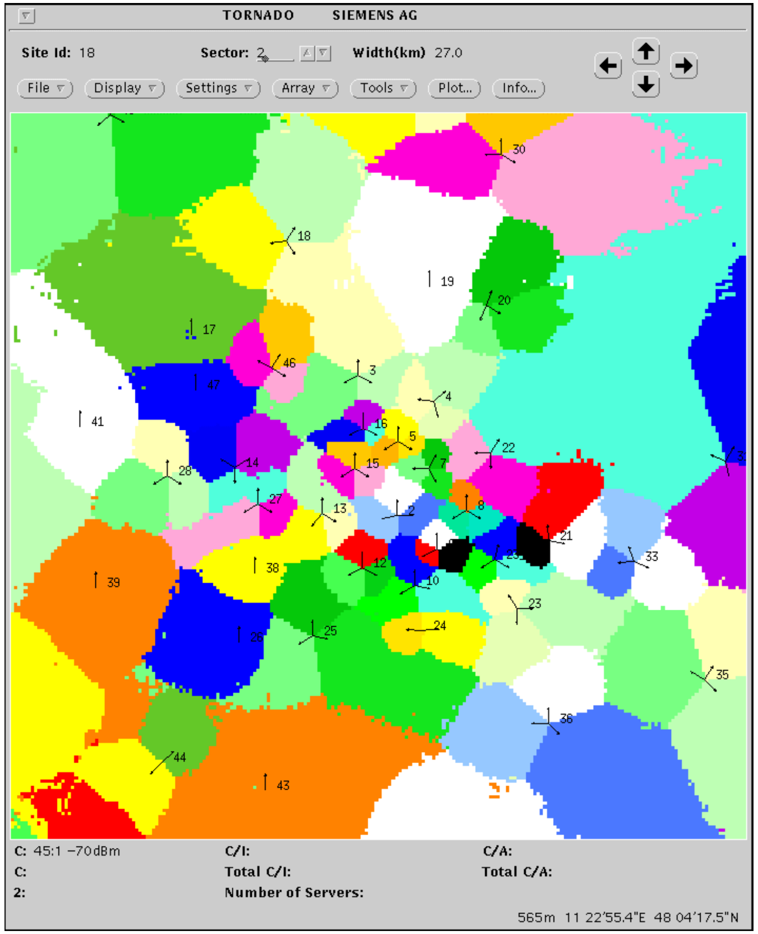
Co-channel cells and Frequency Reuse Distance



- GSM specifications state that system and equipment must operate with specific ratios of carrier to interference:
  - *C/Ic* or useful signal over interfering signal at same frequency may be as low as 9 dB,
  - *C/Ia1* or useful signal over interfering signal at ± 200 kHz may be as low as -9 dB,
  - *C/Ia2* or useful signal over interfering signal at ± 400 kHz may be as low as -41 dB,
  - *C/Ia3* or useful signal over interfering signal at ± 600 kHz may be as low as -49 dB

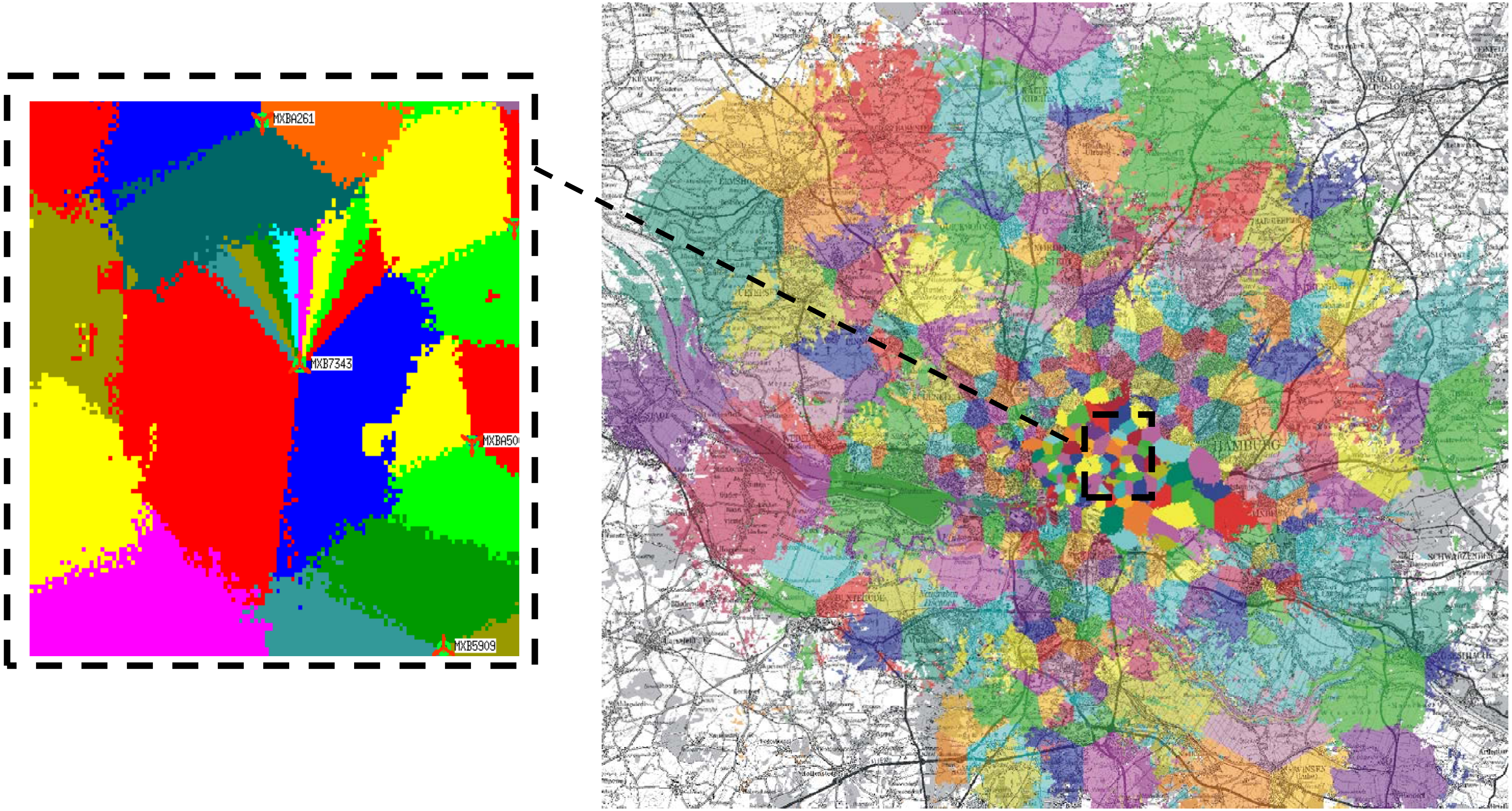
Cellular Concept
Cell Structures & Shapes

- Cells posses very irregular shapes and sizes because of variable propagation conditions.
- Cell size depends on whether it is in an urban, suburban, or rural area.
- Cell boundaries are defined by local thresholds, beyond which the neighboring base station's signal is received stronger than the current one.
- Cell planning: determine the parameters of the cellular topology mathematically, by simulation, and by measurements in order to utilize the available spectrum most efficiently while saving costs.
- Parameters: number of cells, cell size, cluster size, frequency reuse distance, ...



Cell structure of a GSM network (cell color indicates usage of the same set of radio channels)

Cellular Concept
Realistic cell configuration



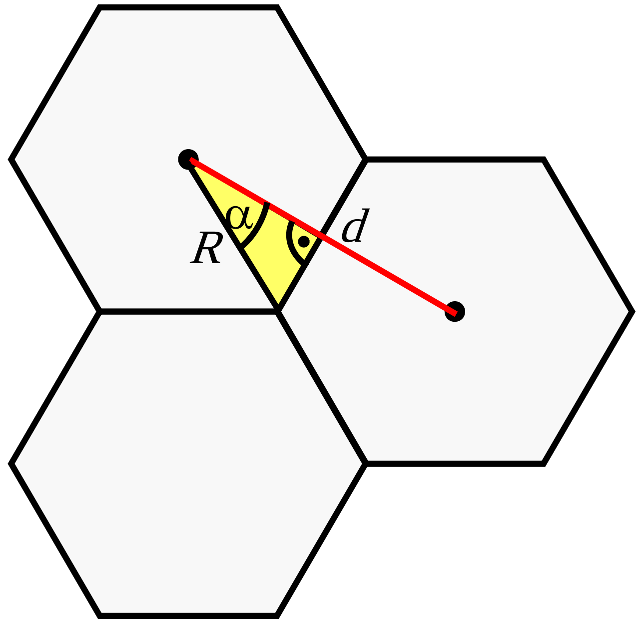
On Cellular Geometry

Geometry of Hexagons
Distance between the Centers of Adjacent Cell

- $R \cong$ radius of a cell (largest possible distance between the hexagon center and its edge)
- $d \cong$ distance between centers of adjacent cells
- $\cos\alpha = \cos 30° = \frac{1}{2}\sqrt{3}$
- $\cos\alpha = \frac{d}{2} \cdot \frac{1}{R}$
- Calculation of d:

$$d = 2R\cos\alpha = 2R\cos 30°$$

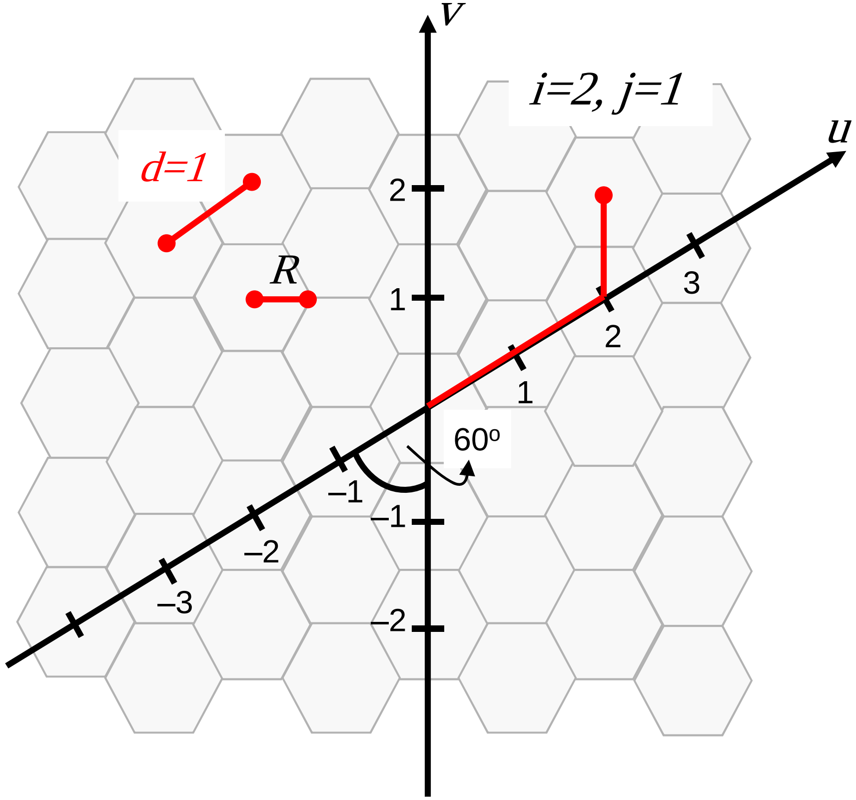
$$\Leftrightarrow d = R\sqrt{3}$$



Geometry of Hexagons

Hexagonal Coordinate System

- Axes u and v intersect at 60º
- Unit scale: distance between two adjacent cells (along the u or v axis) represents one unit, i.e., *d=1*
- Calculation of radius R in the unit coordinate systems
  - $\cos 30° = \frac{1}{2} \cdot \frac{1}{R}$
  - $\Leftrightarrow R = \frac{1}{2\cos 30°}$
  - $\Leftrightarrow R = \frac{1}{\sqrt{3}}$
- Localizing hexagons in a hexagonal coordinate system:
  - Start from a reference cell
  - Move i hexagons along the u-axis
  - Turn 60º
  - Move j hexagons along the v-axis



Geometry of Hexagons

Distance between Co-Channel Cells and Number of Cells per Cluster

- Distance between the centers of two hexagons
  - Use x/y to u/v coordinate transformations:

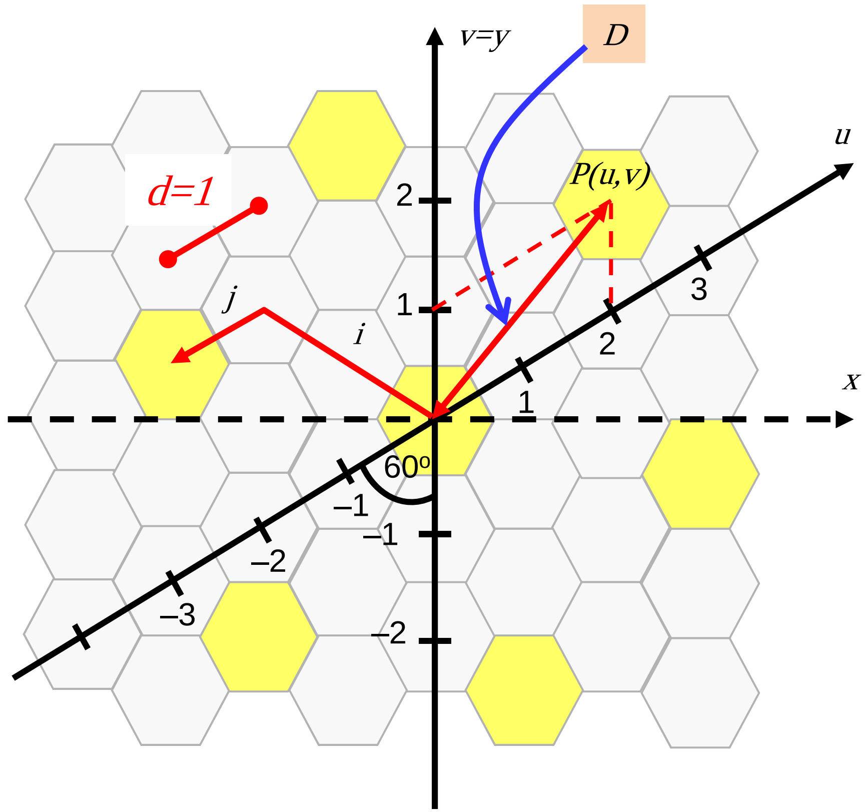
$$r^2 = x^2 + y^2$$
$$x = u\cos 30°$$
$$y = v + u\sin 30°$$
$$r = \sqrt{u^2 + uv + v^2}$$

- In cellular mobile networks, the distance D between co-channel cells (yellow cells in the figure) of adjacent clusters is given by:

$$D = \sqrt{i^2 + ij + j^2}$$

- The number N of cells per cluster is given by:

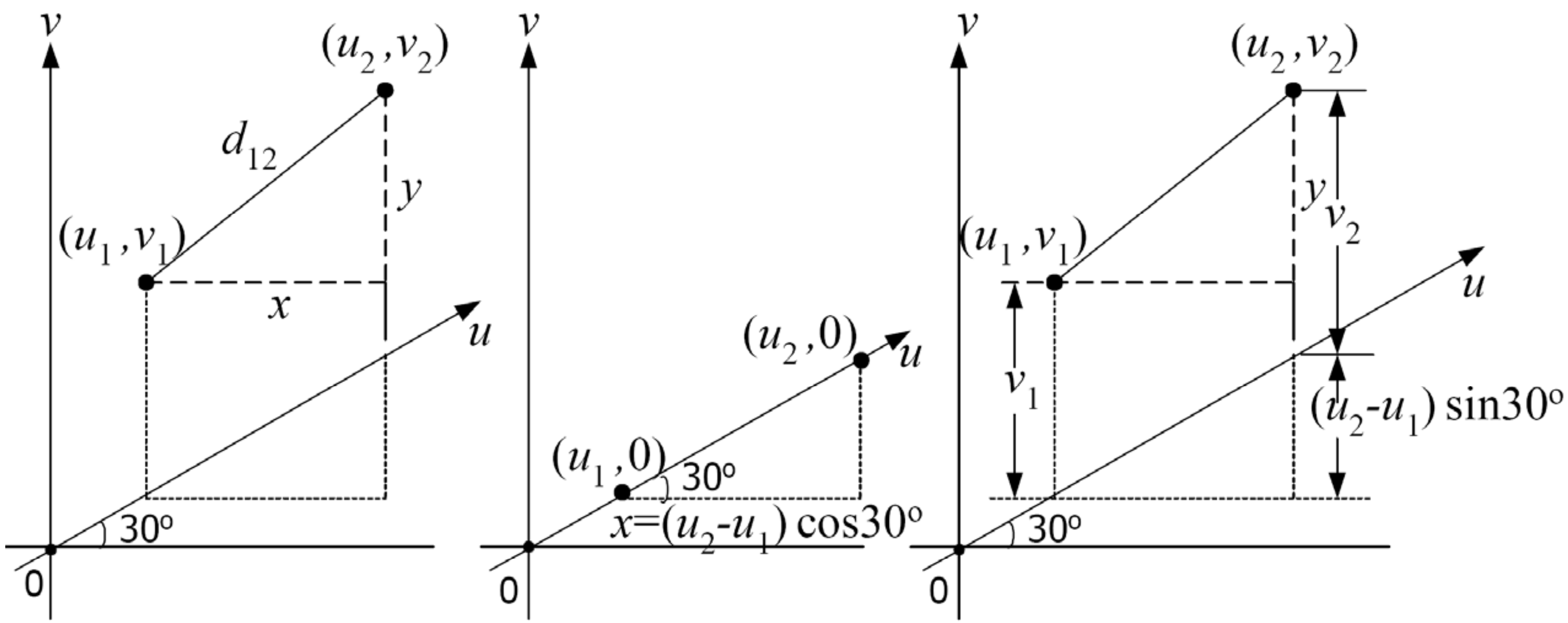
$$N = D^2 = i^2 + ij + j^2$$



Unit scale: distance between two adjacent cells (along the u or v axis) represents one unit, i.e., *d=1*

Geometry of Hexagons

x/y to u/v coordinate systems



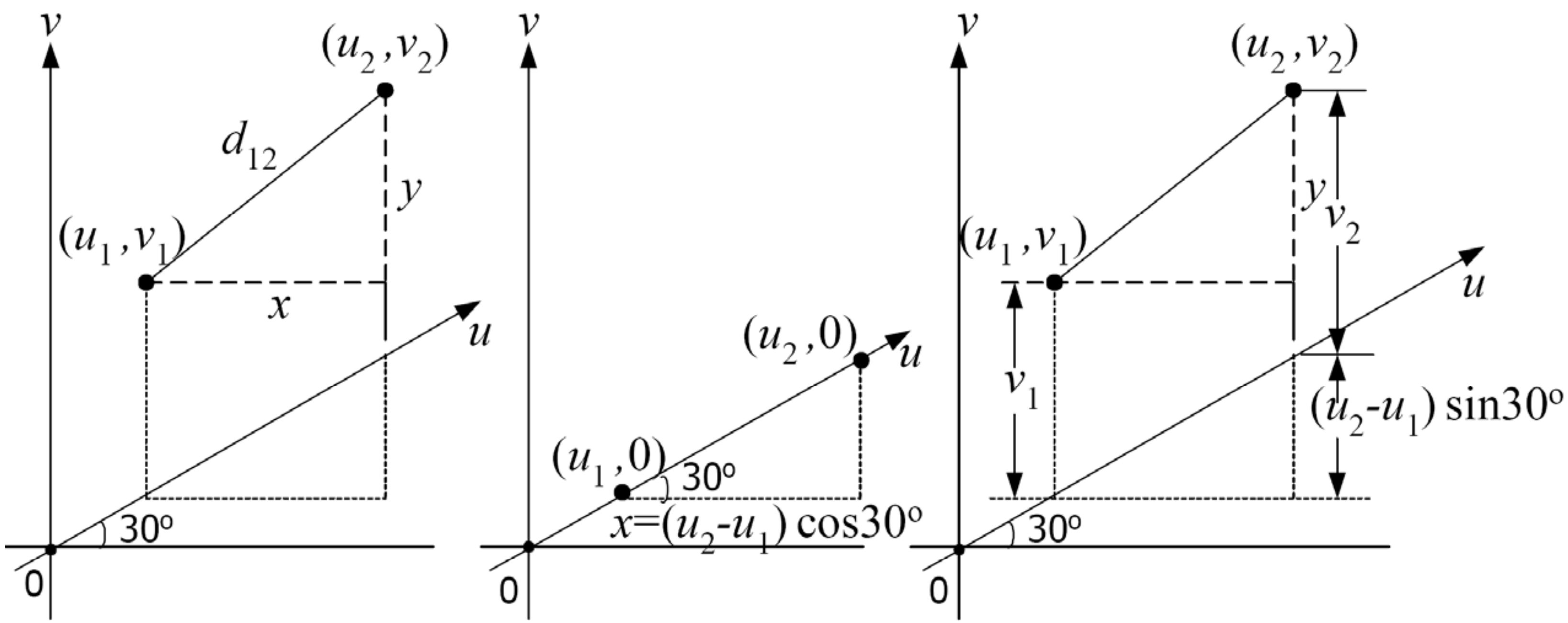
$$x = (u_2 - u_1)\cos 30^o$$

$$y = v_2 + (u_2 - u_1)\sin 30^o - v_1$$

$$d_{12}^2 = x^2 + y^2$$

Geometry of Hexagons

x/y to u/v coordinate systems



Plug x and y in d_{12}:

$$
\begin{aligned}
d_{12}^2 &= \left[(u_2-u_1)\cos 30^o\right]^2 + \left[v_2 + (u_2-u_1)\sin 30^o - v_1\right]^2 \\
&= (u_2-u_1)\cos^2 30^o + (v_2-v_1)^2 + (u_2-u_1)^2 \sin^2 30^o \\
&\quad +2\,(u_2-u_1)\,(v_2-v_1)\sin 30^o \\
&= (u_2-u_1)^2 + (v_2-v_1)^2 + (u_2-u_1)\,(v_2-v_1)
\end{aligned}
$$

Geometry of Hexagons

Distance between Co-Channel Cells and Number of Cells per Cluster

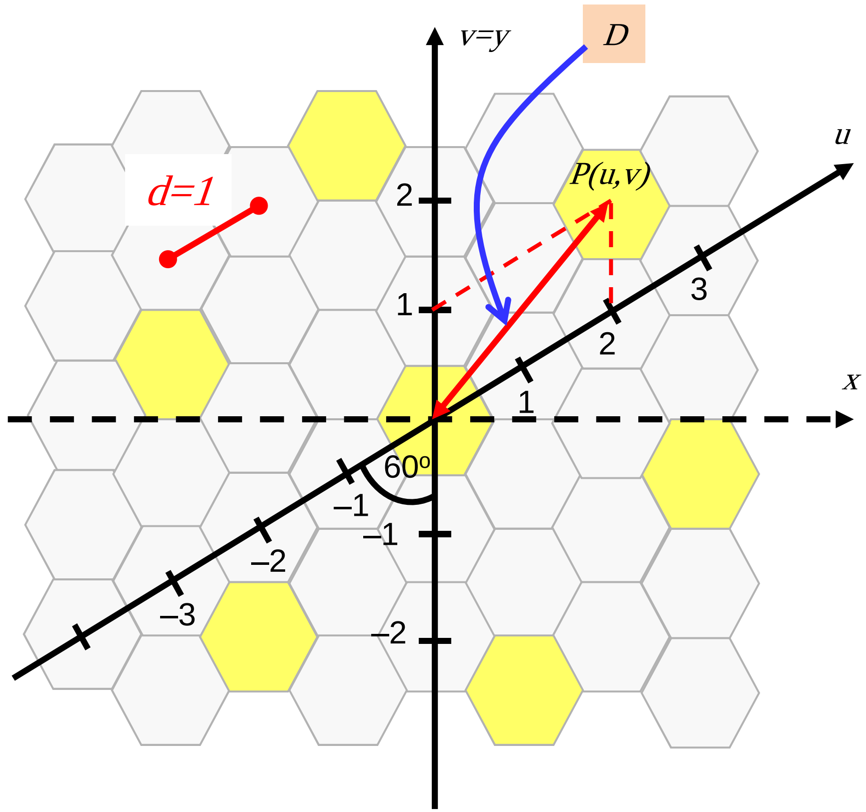
- Let us assume we have a cell at (0,0) and a co-channel cell at (i,j), this means:

$$u_1 = 0 \, , v_1 = 0$$

$$u_2 = i \, , v_2 = j$$

- Then the distance between the centers of cells is (base don last slide):

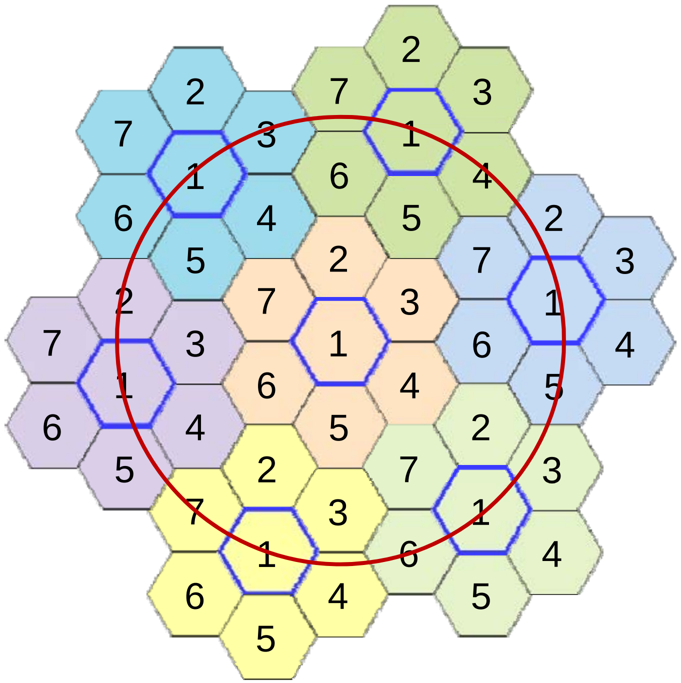
$$D = \sqrt{i^2 + ij + j^2}$$

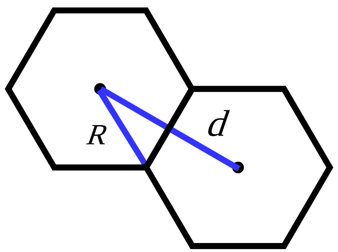


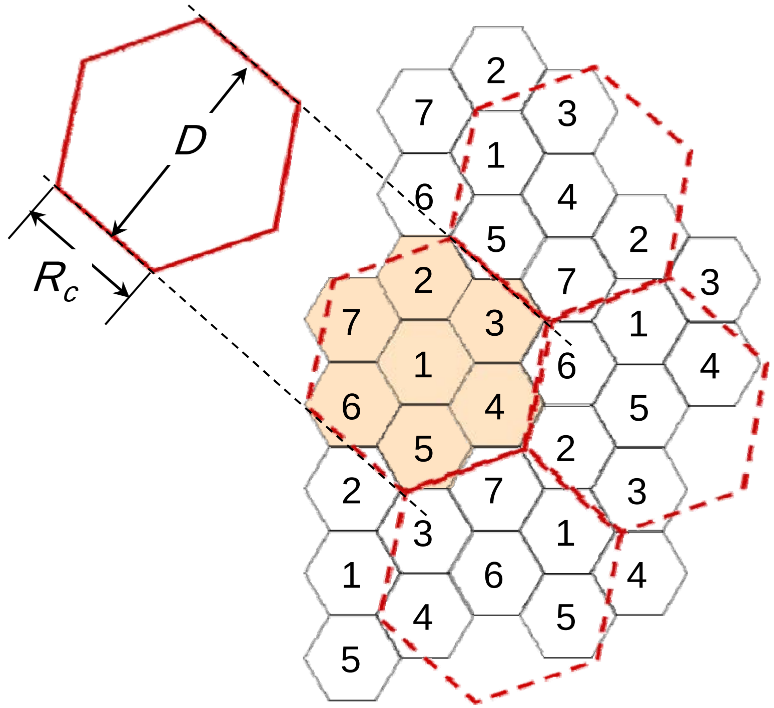
Unit scale: distance between two adjacent cells (along the u or v axis) represents one unit, i.e., $\underline{d=1}$

Cellular Geometry

Defining Cluster Hexagons

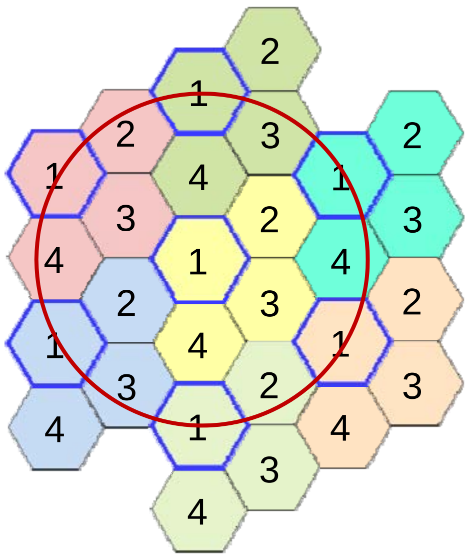


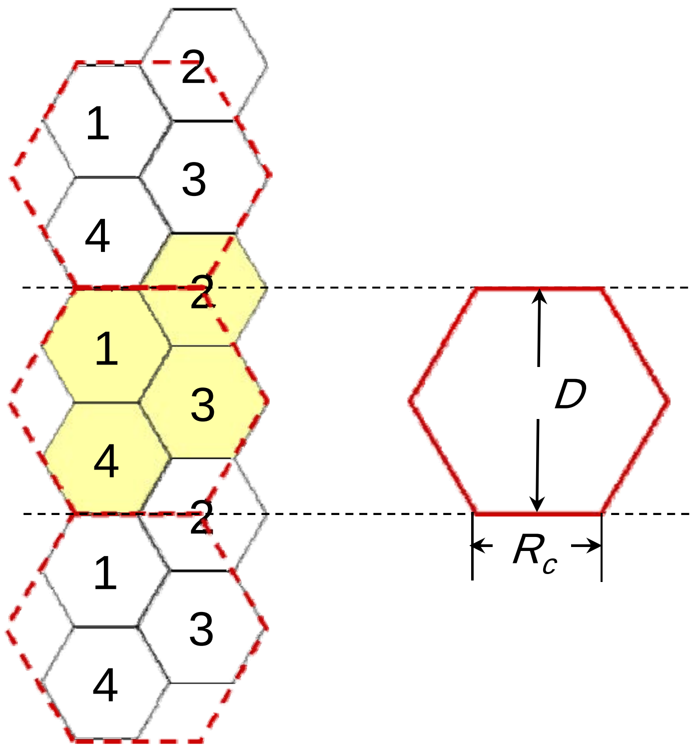


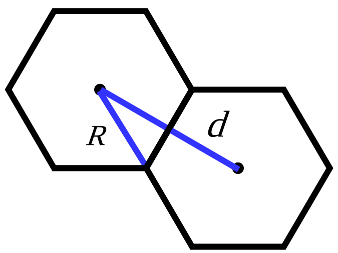


Cellular Geometry

Defining Cluster Hexagons

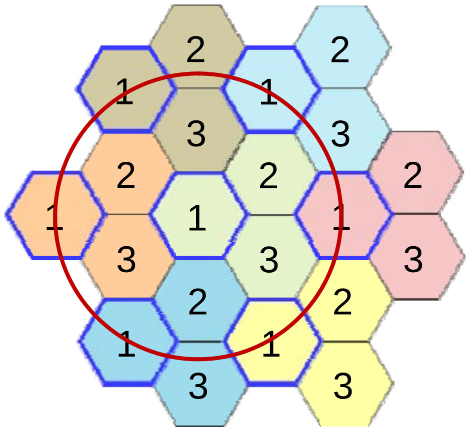


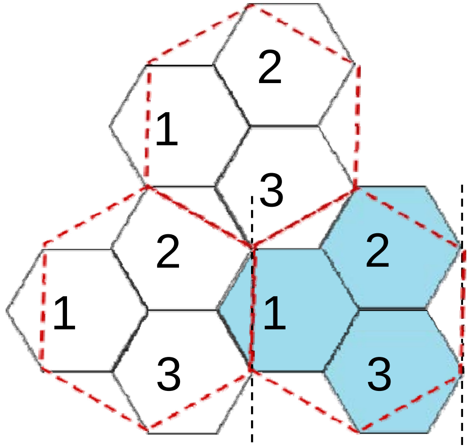


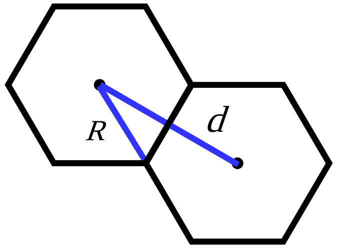


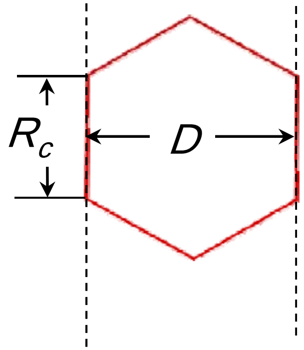
Cellular Geometry

Defining Cluster Hexagons







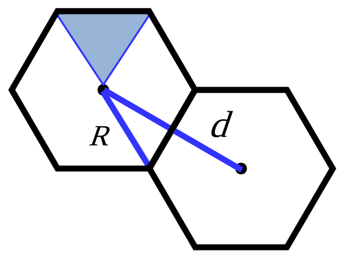


Cellular Geometry

Number of cells in a cluster

- Area of the triangle = $\dfrac{R}{2} R \cos 30° = \dfrac{\sqrt{3}}{4} R^2$

- Area of the hexagon = $6\dfrac{\sqrt{3}}{4} R^2 = \dfrac{3\sqrt{3}}{2} R^2$

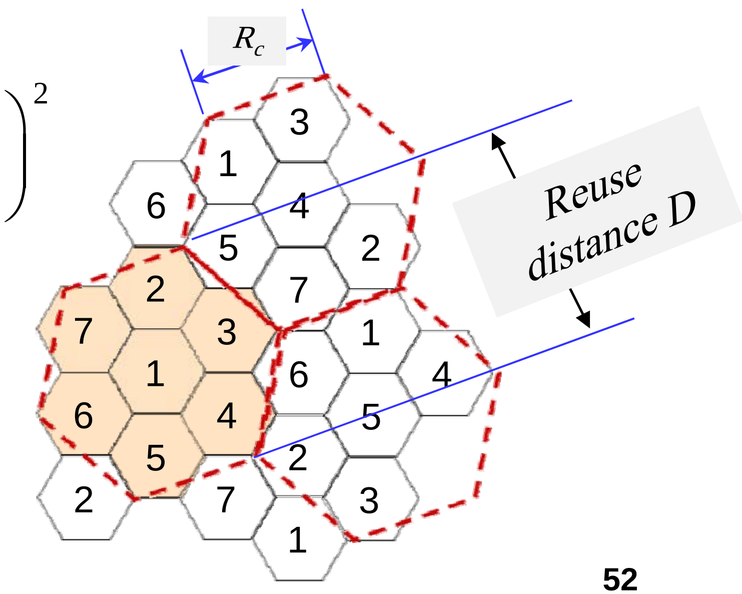


$$d = R\sqrt{3}$$

- Number of cells in a cluster N, Reuse factor q:

$$N = \frac{\text{cluster area}}{\text{cell area}} = \frac{\dfrac{3\sqrt{3}}{2} R_c^{\,2}}{\dfrac{3\sqrt{3}}{2} R^{\,2}} = \frac{D^{\,2}}{3R^{\,2}} = \frac{1}{3}\left(\frac{D}{R}\right)^2$$

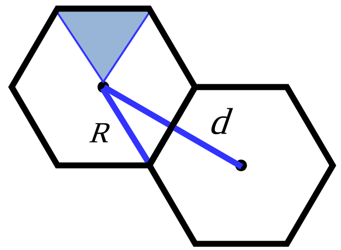
$$\Rightarrow q = \frac{D}{R} = \sqrt{3N}$$



Cellular Geometry

Number of cells in a cluster

- With a normalized distance between adjacent cells (d=1), it follows:

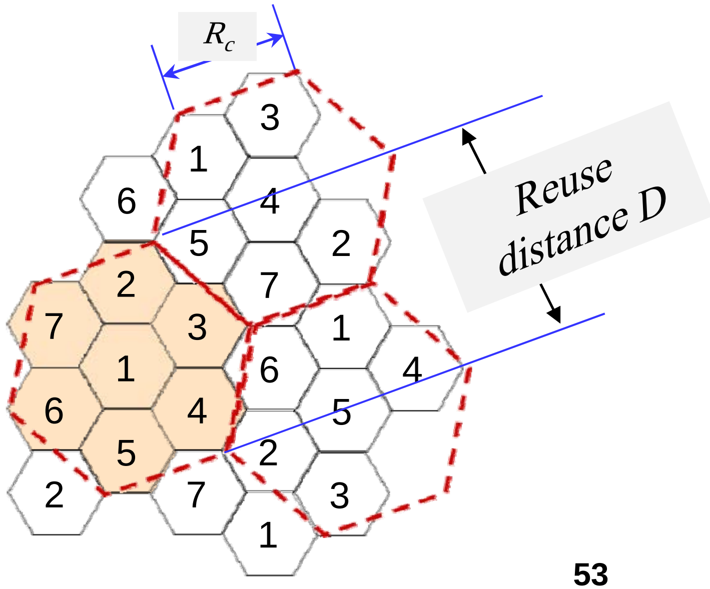


$$d = R\sqrt{3}$$

$$R = \frac{1}{\sqrt{3}}$$

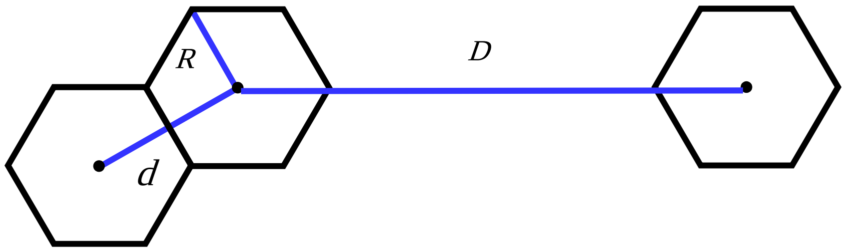
$$\frac{D}{R} = \sqrt{3N} \Rightarrow D = N^{2}$$

$$\Rightarrow N = \sqrt{i^{2} + ij + j^{2}}$$

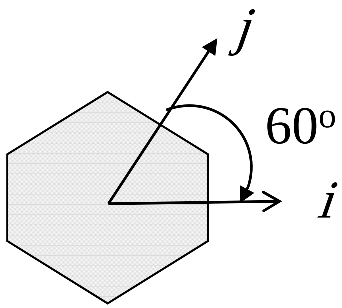


Cellular Concept

Summarized formula



D = Reuse distance (distance to nearest cell with same frequency)
R = Cell Radius
d = Distance to adjacent cell
N = Cluster size
q = Reuse factor;
= Co-channel interference reduction factor



- N = 1, 3, 4, 7, 9, 12, 13, etc.

Popular values: 4 and 7.

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

In a system with $d = 1$:

$$D = \sqrt{i^2 + ij + j^2} = \sqrt{N}$$

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

i and j are integers.

Frequency reuse patterns

i	j	N	q=D/R
1	0	1	1.73
1	1	3	3.00
2	0	4	3.46
2	1	7	4.58
3	0	9	5.20
2	2	12	6.0
3	1	13	6.24
4	0	16	6.93
3	2	19	7.55
4	1	21	7.94
4	2	28	9.17

Supplementary Material
“Antenna Basics”

Antennas
Overview

Antenna

- Electrical conductor used either for radiating electromagnetic energy into space (transmission) or for collecting electromagnetic energy from space (reception)
- **Transmission**: Antenna converts electrical signals on a cable into electromagnetic waves
- **Reception**: Antenna converts energy from passing electromagnetic waves to an electrical signal on the cable
- Electric and magnetic fields are rapidly changing (according to the signal's desired frequency) and propagate outward through space at the speed of light

  $c = 3 \times 10^8$ m/sec

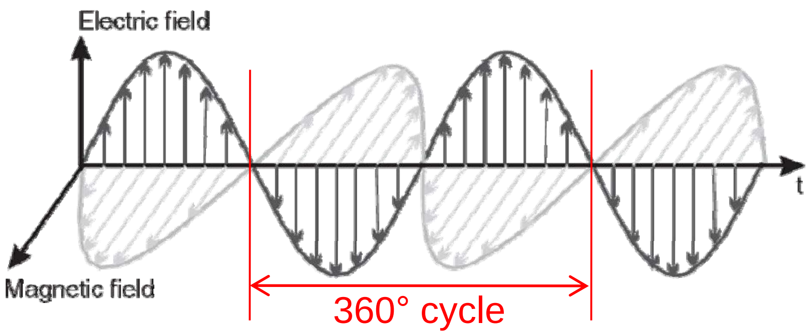
- Dimensions of an antenna depend on the wavelength of the radio signal being transmitted or received

Wavelength

- One 360 degree cycle
- Distance in space between two points in a periodic wave that have the same phase
- Conversion of frequency into wavelength:

$$\lambda = \frac{c}{f}$$

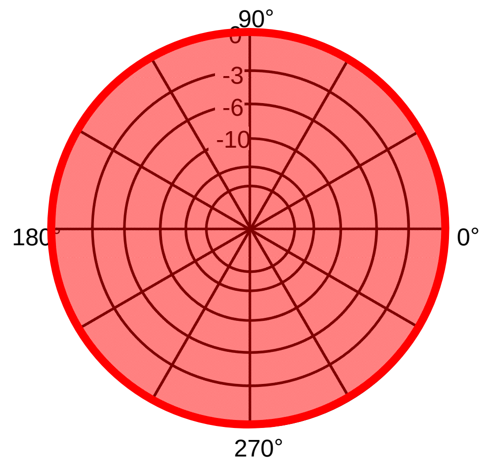
λ: Wavelength in meters
c: Speed of light
f: Frequency in Hertz



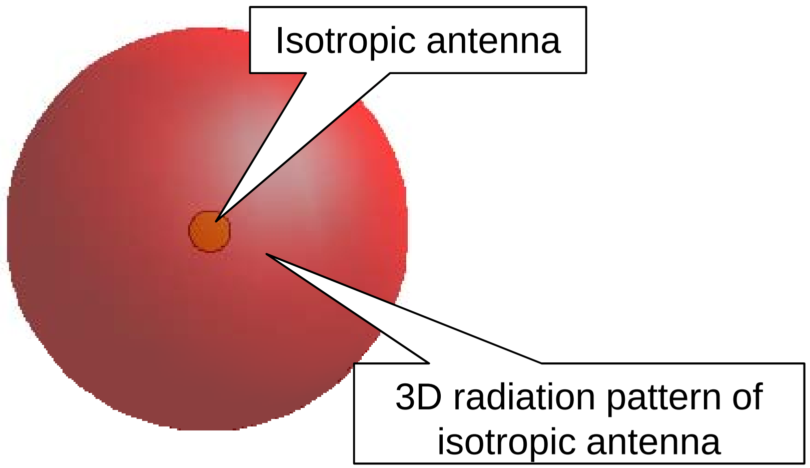
Antennas
Isotropic Antenna

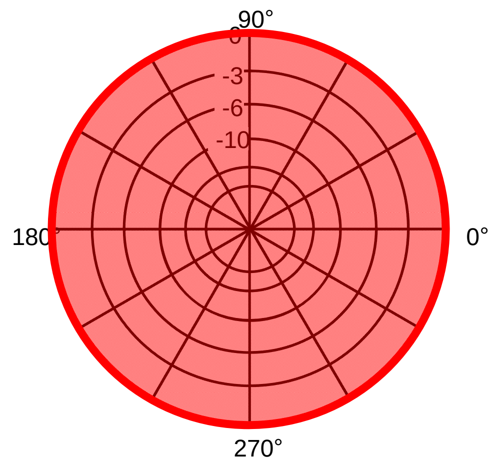
Isotropic antenna

- Idealized antenna (does not exist in reality)
- Single point that radiates power in all directions equally
- All points with equal power are located on a sphere with the antenna at its center
- Used as a reference antenna for determining the **gain** of antennas



Horizontal plane





Vertical plane

Antennas
Radiation Patterns of Antennas

Radiation pattern

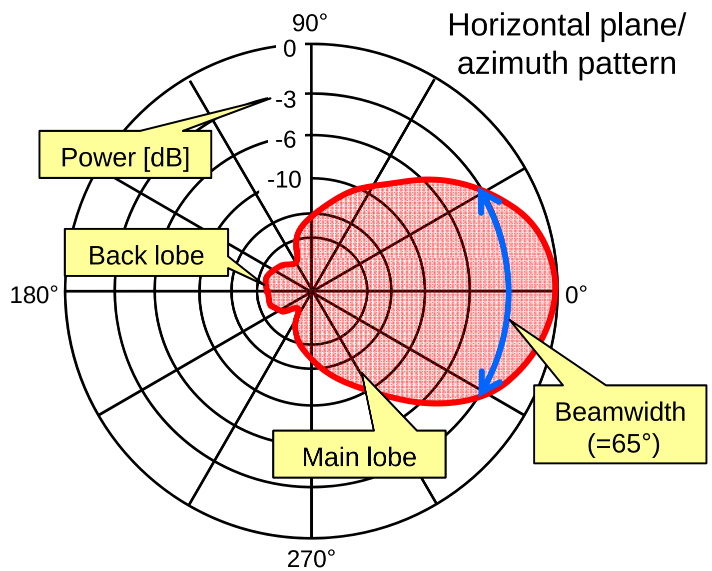
- 3D-plot of the field strength (voltage/meter) or the power density (watt/square meter) measured at various angular positions of constant distance to the antenna
- **Horizontal plane/azimuth pattern**: pattern as observed when looking at it from directly above the antenna
- **Vertical plane/elevation pattern**: pattern as observed when looking at it from the side

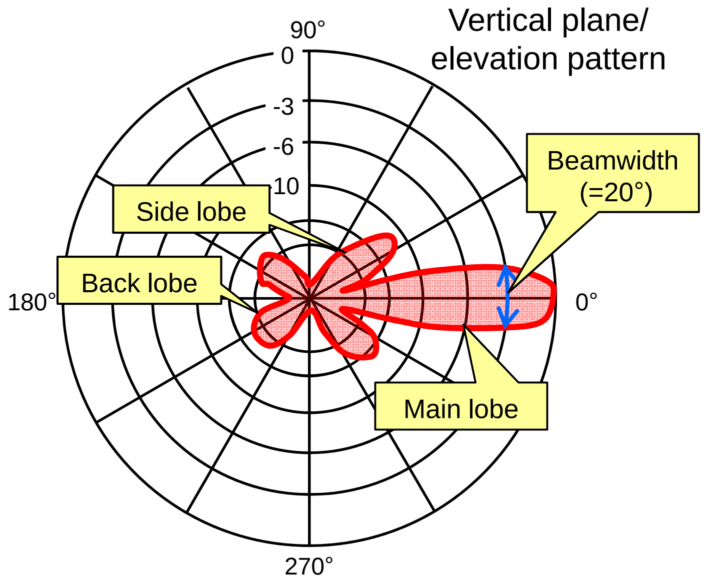
Beamwidth

- Directional antennas direct a beam of radiation in one or more directions (**main lobes**)
- Beamwidth is defined as the angle between the half-power points of the main lobe

Front-to-back ratio

- Direction of maximum radiation in the horizontal plane is considered to be the *front* of the antenna, and the back is the direction 180º from the front

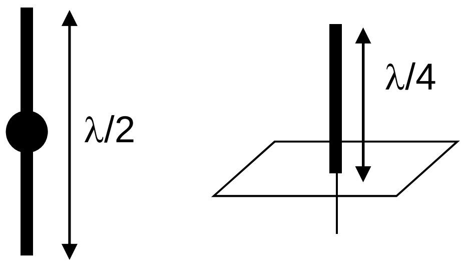


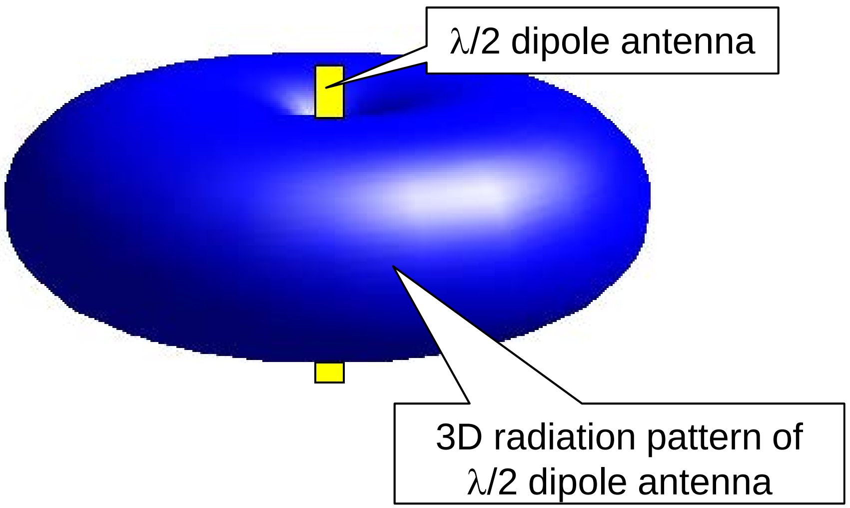


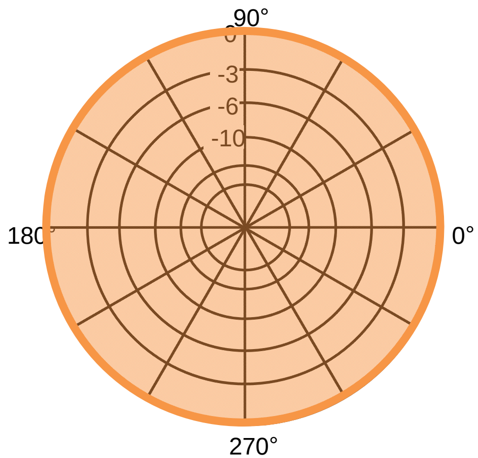
Antennas
Dipole Antenna

λ/2-dipole antenna

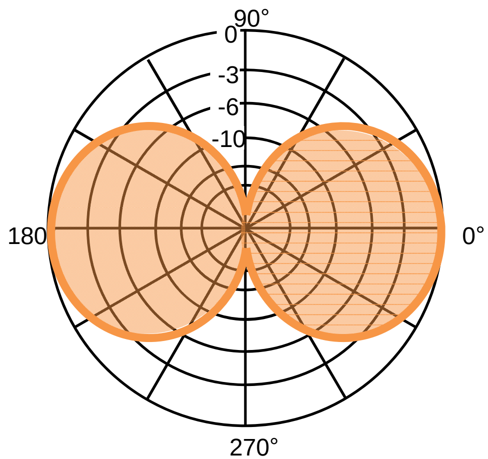
- Simplest real antenna with λ/2 length (λ/4 if mounted on the roof of a car)
- Omnidirectional radio pattern in one plane and figure-eight patterns in the other planes







Horizontal plane



Vertical plane

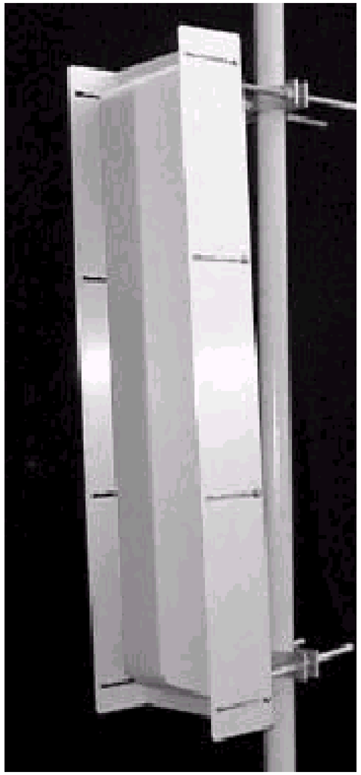
Antennas
Antennas of Mobile Devices

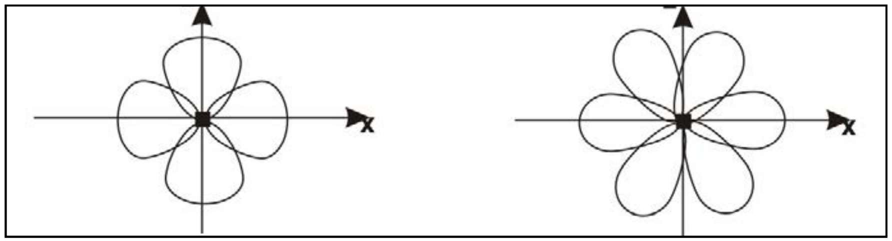
- Antenna dimensions are normally multiples of a quarter or half the wavelength of the signal to be transmitted or received
- Example: if a mobile phone operating in the GSM 900 MHz band, a half-wave dipole would need to be 333.3 mm (one third of a meter) in length
- Difficult to use and not truly hand portable
- Quarter and even one-eight wave dipoles can be used
- Size can be further reduced in length by designing them in form of a helix, which has the overall correct electrical length but is packed into a smaller physical space

Antennas
Sectoral Antennas

Sectoral Antennas

- Directional in nature
- Can be adjusted from 45° to 180°
- Typical gains between 10 to 19 dBi
- Commonly used for cellular networks





Antenna Gain

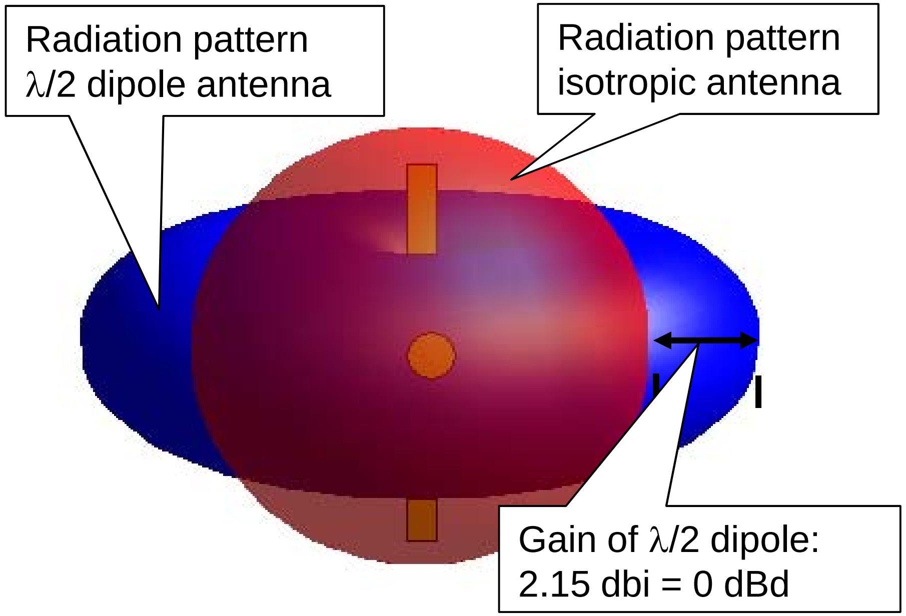
- Measure for the directionality of an antenna
- Defined as the power output, in a particular direction, compared to that produced in any direction by a perfect isotropic antenna

$$G = \frac{\text{Maximum power of antenna}}{\text{Power of isotropic antenna}}$$

- Power density at a distant point from an antenna with gain Gt is the power density from an isotropic antenna multiplied with the gain of the transmitting antenna:

$$P_D = \frac{P_t G_t}{4\pi d^2}$$

- Antenna gain is often expressed as **dezibel isotrop** (dBi) or **dezibel dipole** (dBd)



Isotropic antenna	0 dBi = factor 1
λ/2 dipole	2.15 dBi = factor 1,64
Sector antenna in cellular networks	18 dBi = factor 63
Radio link antenna	30 dBi = factor 1000

Friis Free Space Equation

Friis Free Space Equation

- Prediction of received signal strength when transmitter and receiver have a clear, unobstructed LoS path between them
- In its simplest form, Friis free space equation is given by

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi d} \right)^2$$

P_r: received power

P_t: transmitted power

G_r: gain of receiving antenna

G_t: gain of transmitting antenna

d: distance between transmitting and receiving antenna

λ: wavelength

Harald T. Friis
Danish electrical engineer
1893-1976
Published his well-known analytic formula for transmission loss, the Friis transmission equation, in 1946
Picture: IEEE

Distance Power Relationship

- Free space model does not hold for all environments, as the signal travels from the transmitter to the receiver along a single path
- In realistic scenarios, the signal reaches the receiver through several different paths (multipath propagation)
- In a simple model, the received signal strength is calculated considering the distance between antenna and receiver and the distance-power gradient (or path-loss gradient):

$$P_r = P_0 d^{-\alpha}$$

P_0: received power at a reference distance of 1 meter

α: distance-power gradient (=2 for free space); depends on environment

- Distance-power relationship in dB is given as

$$10\log(P_r) = 10\log(P_0) - 10\alpha\log(d)$$

- Total path loss in dB is given as

$$L_p = L_0 + 10\alpha\log(d)$$

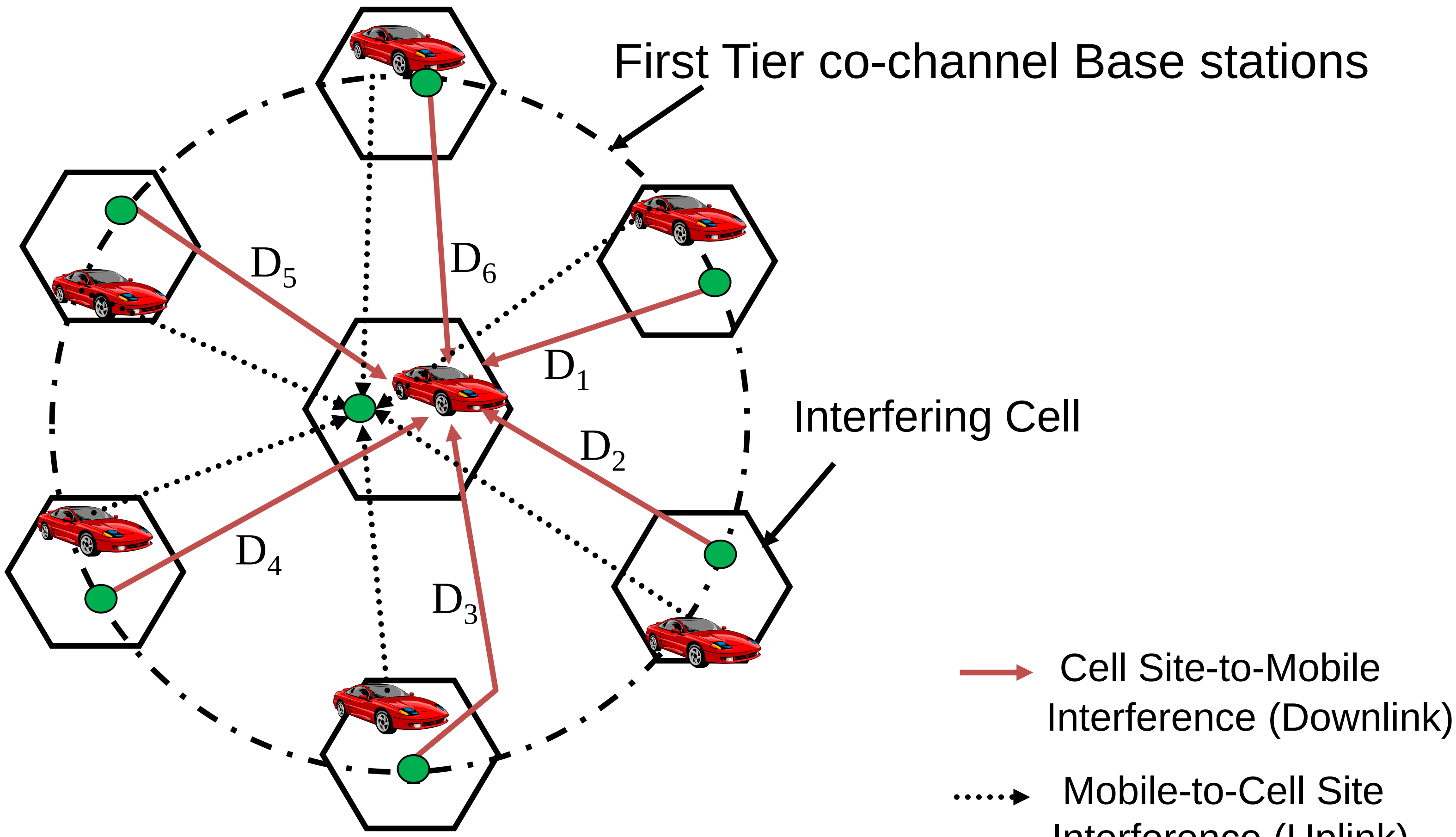
with

$$L_0 = 10\log(P_t) - 10\log(P_0)$$

Environment	α
Free space (vacuum)	2
Urban cells	2.7 to 3.5
Urban cells (shadowed)	3 to 5
In building, line-of-sight (LOS)	1.6 to 1.8
In building, obstructed path	4 to 6
In factory, obstructed path	2 to 3

Cellular Concept

Co-channel Interface with Omni-directional Cell Site



Cellular Concept

Calculation of Co-Channel Interference

- Co-channel interference is measured as signal-to-noise ratio:

$$SNR = \frac{\text{useful signal}}{\text{disturbing signal}} = \frac{\text{useful signal}}{\text{neighbor cell interference} + \text{noise}}$$

- Intensity of co-channel interference depends on the cell radius and the frequency reuse distance
- **Assumptions**: Size of each cell is approx. the same and the base stations transmit the same power

Transmit power of serving base station

Path loss at distance R (=radius)

$$SNR = \frac{P_0 R^{-\alpha}}{\sum_{i=1}^{6} P_i + n} \approx \frac{P_0 R^{-\alpha}}{\sum_{i=1}^{6} P_0 D^{-\alpha} + n} = \frac{P_0 R^{-\alpha}}{6 P_0 D^{-\alpha} + n}$$

Other noise

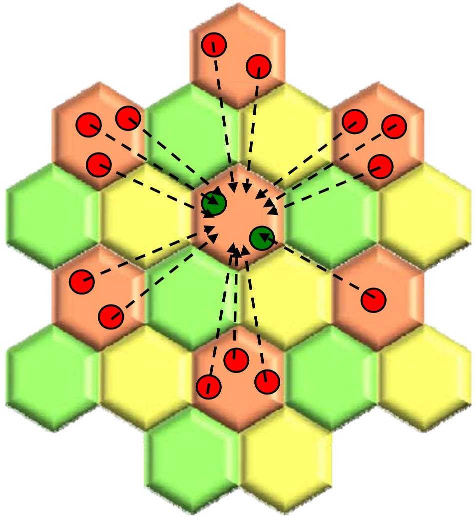
Six co-channel cells in a hexagonal structure

Received power from co-channel cells

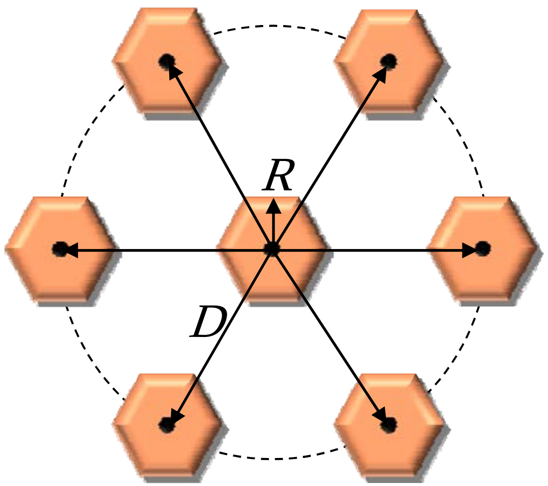
Path loss at distance D (=frequency reuse distance)

- Neglecting the noise *n* results in an approximation of the co-channel interference:

$$SNR \approx \frac{R^{-\alpha}}{6D^{-\alpha}} = \frac{1}{6}\left(\frac{R}{D}\right)^{-\alpha}$$



Interfering transmitters



Distances of co-channels

SNR and Cluster Size

- Sufficient isolation between cells is needed to reduce co-channel interference
- Increasing the signal power by the same amount in all cells does not have an impact on the co-channel interference
- Spatial separation between cells is increased if:
  - the radius *R* of a cell is reduced,
  - the frequency reuse distance *D* is increased
- Co-channel reuse ratio $q = \frac{D}{R}$ should be maximized
- In hexagonal geometry: $q = \sqrt{3N}$

- Determination of frequency reuse distance *D:*
  $D = R\sqrt{3N}$
- Ratio of co-channel interference:

$$SNR = \frac{R^{-\alpha}}{6D^{-\alpha}} = \frac{R^{-\alpha}}{6\left(R\sqrt{3N}\right)^{-\alpha}} = \frac{1}{6}(3N)^{\frac{\alpha}{2}}$$

- Ratio of co-channel interference for good speech understandability: *18 dB*

- Determination of minimum cluster size (assuming a path-loss gradient of α=4):

$$10\log SNR \geq 18 \text{ dB}, \quad SNR \geq 63.1 \quad \Rightarrow D \approx 4.4R$$

$$\frac{1}{6}(3N)^{\frac{\alpha}{2}} = SNR \geq 63.1 \quad \Rightarrow N \geq 6.5 \Rightarrow N = 7$$

Increasing the Capacity of Cellular Systems
Overview

Motivation

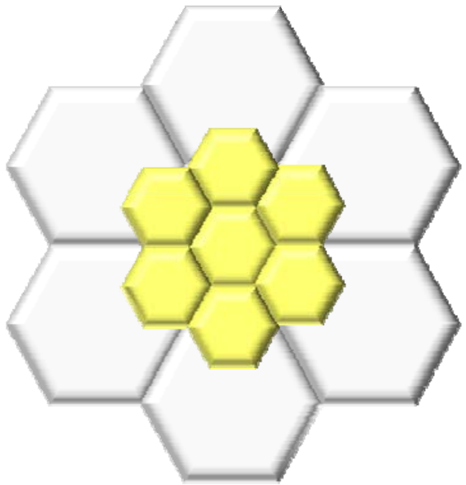
- Main investment of a cellular network is the cost of the infrastructure including
  - the cost of base stations and switching equipment,
  - property (land for setting up the cell sites),
  - installation, and
  - links connecting the base stations
- Costs are proportional to the number of base stations
- All network operators start their operation with the minimum number of cell sites to cover a geographic area that requires the least initial investment
- As the number of subscribers increases, network operators must acquire new cell sites to increase the capacity of the network and to support new subscribers

Methods

- Obtain additional spectrum for new subscribers
  - Simple but expensive
- Change the cellular topology
  - Cell splitting
  - Cell sectoring
- Change the frequency allocation methodology
  - Non-uniform distribution of radio channels among different cells according to their traffic needs
  - Dynamic allocation of channels to cells
- Change the modem and access technology
  - Migration requires the user to purchase new terminals and the operator to install new components

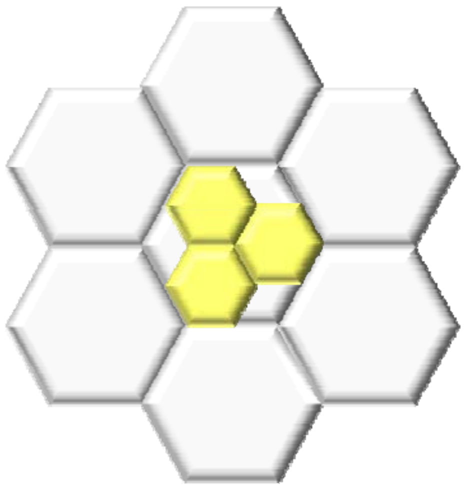
Increasing the Capacity of Cellular Systems
Cell Splitting

- Process of subdividing a congested cell into smaller cells, each with its own base station and a reduction in transmit power
- Cell splitting increases the capacity since it increases the number of times that channels are reused
- Replacing cells by smaller cells increases the number of channels per unit area
- Increased number of cells would increase the number of clusters over the coverage region



Example

- If the radius of the new smaller cells is *R/2* (where *R* is the radius of the old cells), capacity increases by four times

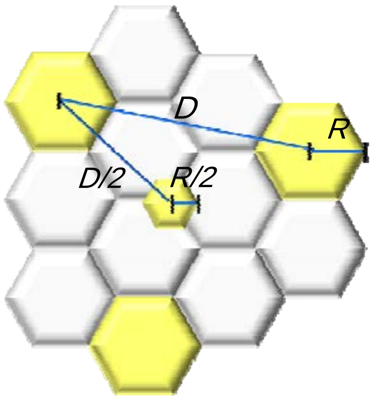


Increasing the Capacity of Cellular Systems
Problems of Cell Splitting

- In practice, not all cells are split at the same time
- Different cell sizes exist at the simultaneously
- Channel assignment becomes more complicated as the co-channel reuse ratio changes

Example

- Assumptions: radius of small cells is *R/2* and frequency reuse distance between small and large cells is *D/2*



Scenario A

- Transmit power in small cells is the same as the transmit power in large cells
- Co-channel interference in the small cell is maintained, because the co-channel ratio is

$$q = \frac{D/2}{R/2} = \frac{D}{R}$$

- Co-channel interference in large cells increases, because the co-channel is only

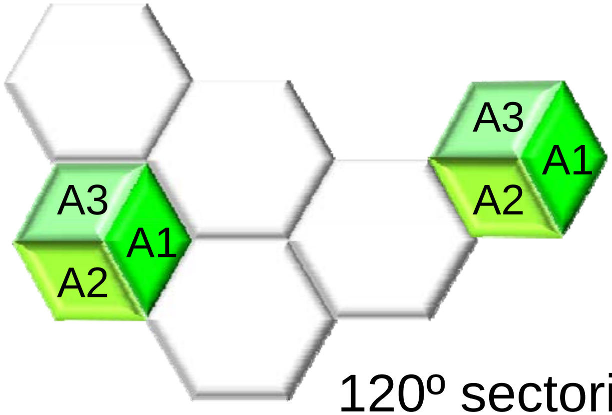
$$q = \frac{D/2}{R}$$

Scenario B

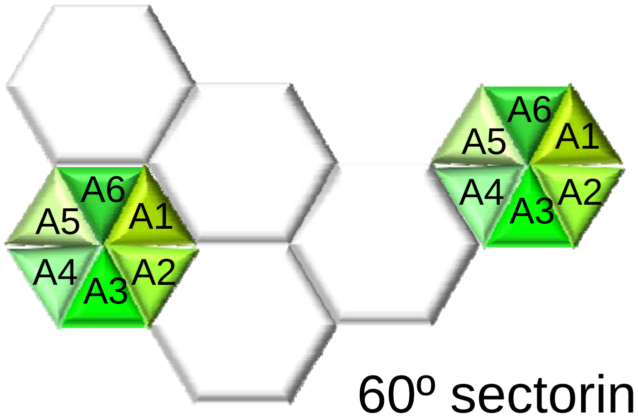
- Transmit power of smaller cells is halved
- Co-channel interference of large cells is maintained, but co-channel interference in small cells increases

Increasing the Capacity of Cellular Systems
Cell Sectoring

- **Cell splitting**: increase the capacity by decreasing the cell radius R and keeping the co-channel ratio $q=D/R$ unchanged
- **Cell sectoring**: increase the capacity by keeping the cell radius R unchanged and decreasing q
- Omni directional antenna at the base station is replaced by several directional antennas, each radiating within a specified sector
- A given cell will receive interference and transmit with only a fraction of the available co-channel cells
- The factor by which the co-channel interference is reduced depends on the amount of sectoring used
- A cell is normally partitioned into three 120º sectors or six 60º sectors



120º sectoring



60º sectoring

Increasing the Capacity of Cellular Systems
Cell Sectoring

Example

- Interference experienced by a mobile terminal located in the right-most sector in the center cell A0
- Assumption: cluster with seven cells and 120º cell clusters
- Three co-channel cell sectors A1, A2, A3 to the right of the center cell, and three co-channel cells A4, A5, A6 to the left of the center cell
- Out of these six co-channel cells, only A5 and A6 have sectors with antenna patterns which radiate into the center cell
- Mobile in the center cell experiences co-channel interference only from A5 and A6
- Co-channel interference is significantly reduced compared to omnidirectional antennas
- Reduction of co-channel interference allows to decrease the cluster size *N* in order to improve frequency reuse