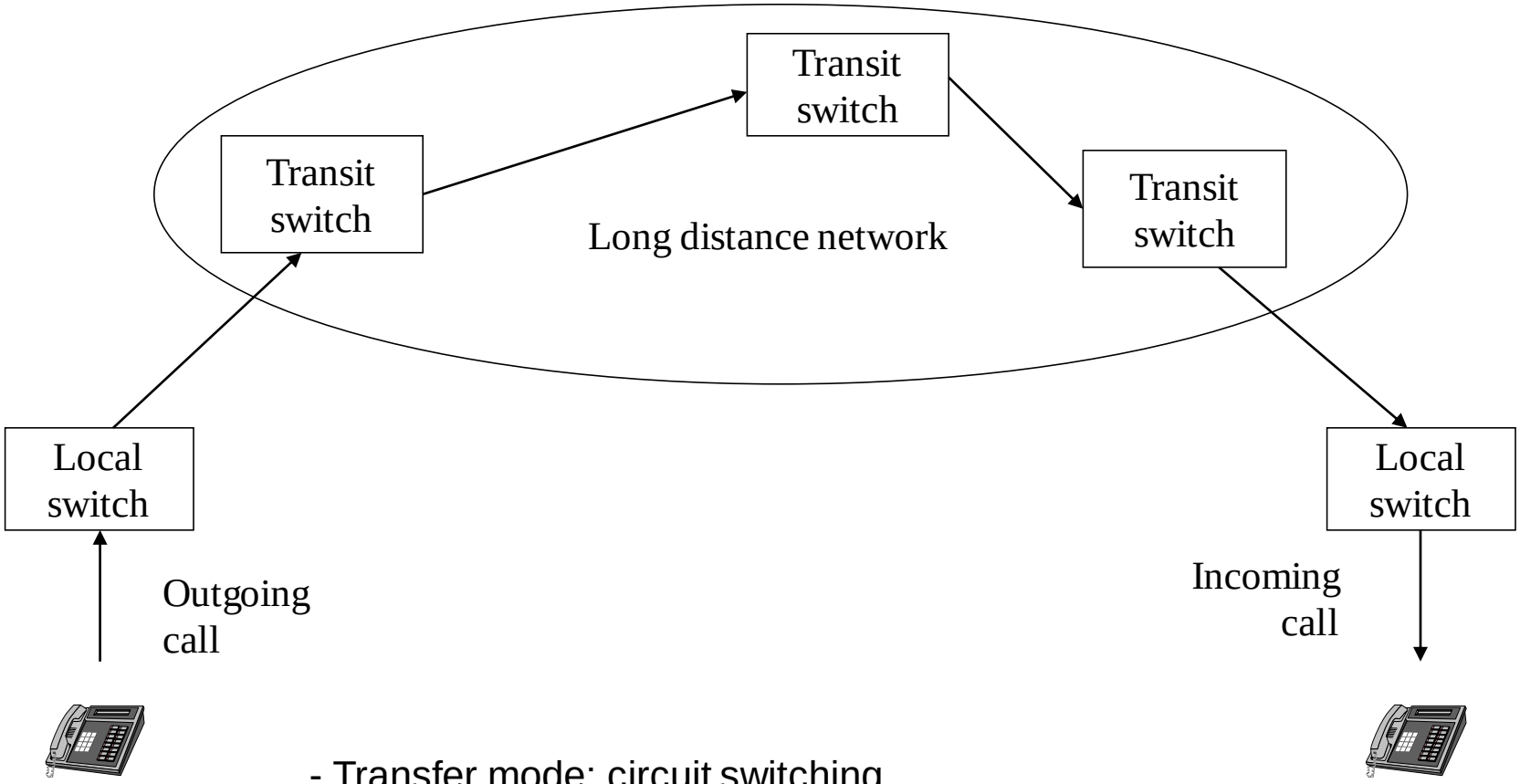
Wireless Communication
Session 3
Cellular Design

M. Daneshvar Farzanegan

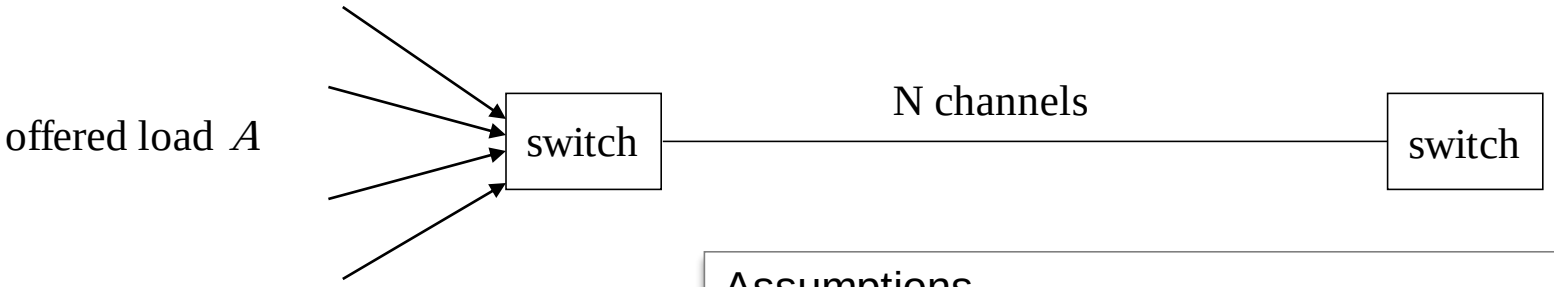
Soourosh.blogfa.com
smdanesh@yahoo.com

Public Switched Telephone Network - PSTN (reminder)



- Transfer mode: circuit switching
- All the network (except part of the access network) is digital
- Each voice channel is usually 64kb/s

PSTN Trunk Dimensioning (reminder)



Assumptions

- Loss system: if the N channels are busy, any additional call is dropped
- Independent sources

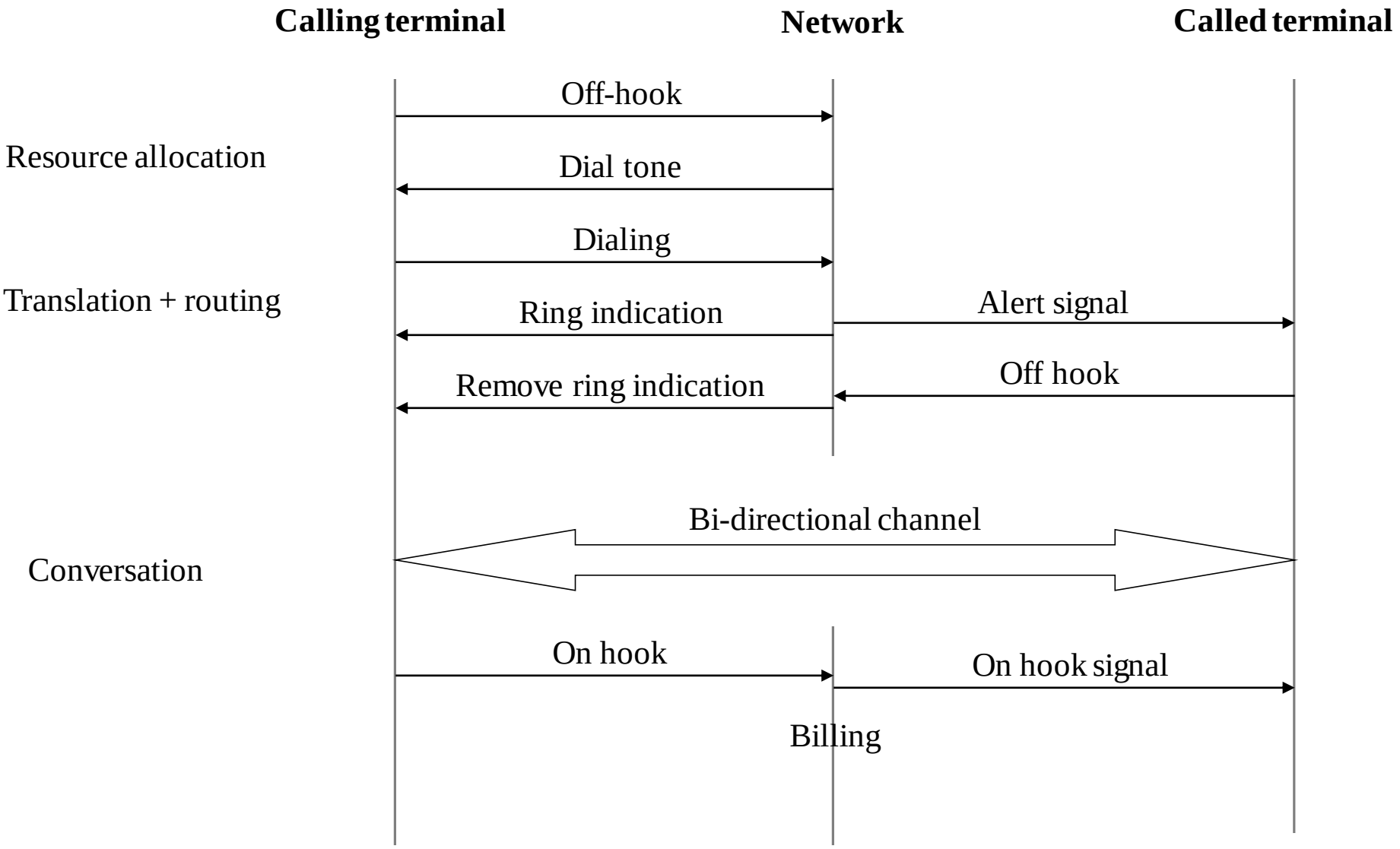
$$A = \lambda \cdot E[X] \text{ [Erlangs]}$$

where X = call duration [sec/call]
Y = call arrival [calls/sec] ~ Poisson(λ)

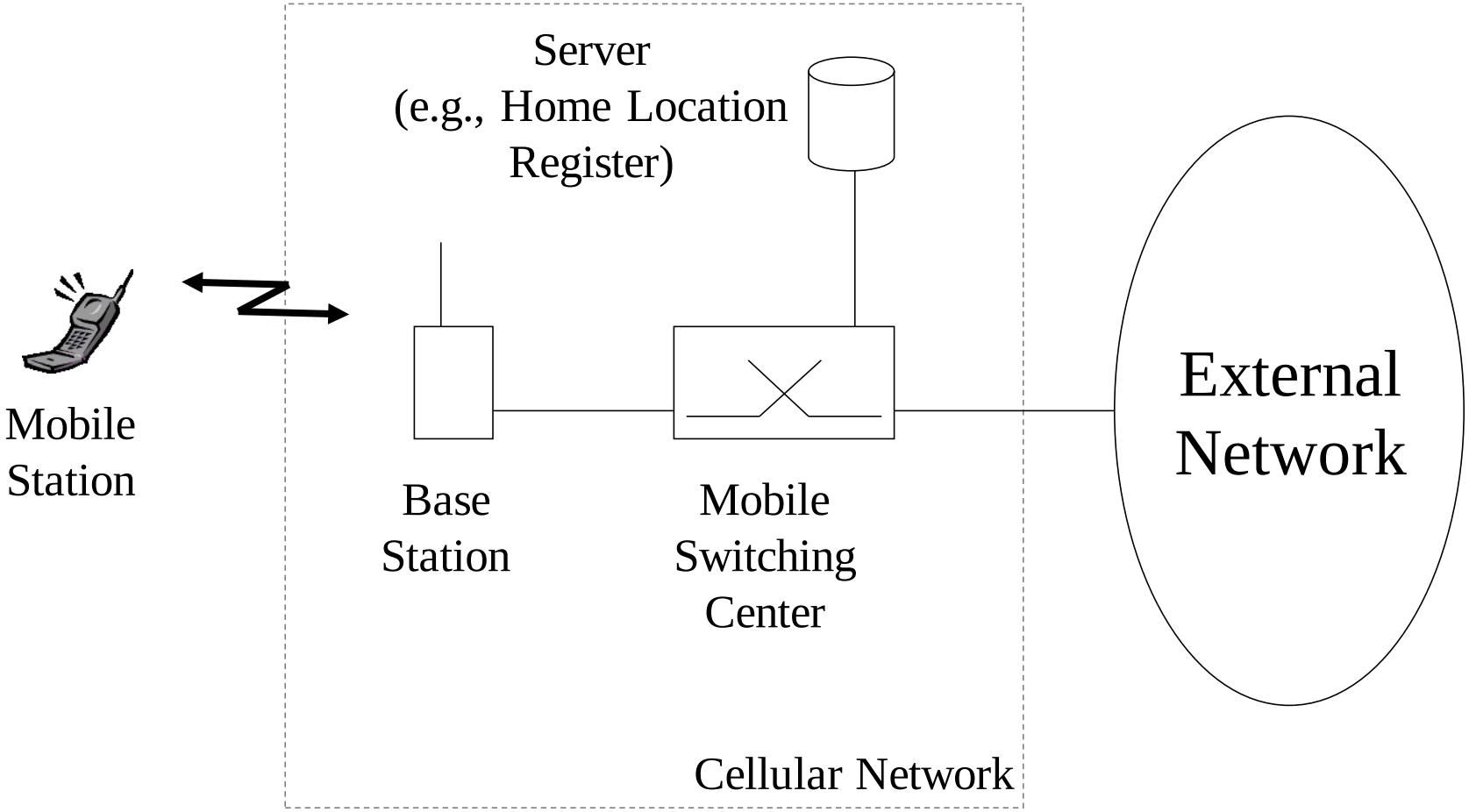
$$\Pr_{Blocking} = \Pr(\text{"call dropped because line busy"}) = \text{Erlang-B}(A, N) = \frac{A^N}{N! \sum_{i=0}^{N} \left(\frac{A^i}{i!} \right)}$$

$$\text{Each channel N carries a traffic } \rho = \frac{\left(1 - \Pr_{Blocking}\right) A}{N}$$

Basic Call (reminder)



Architecture of Cellular Networks



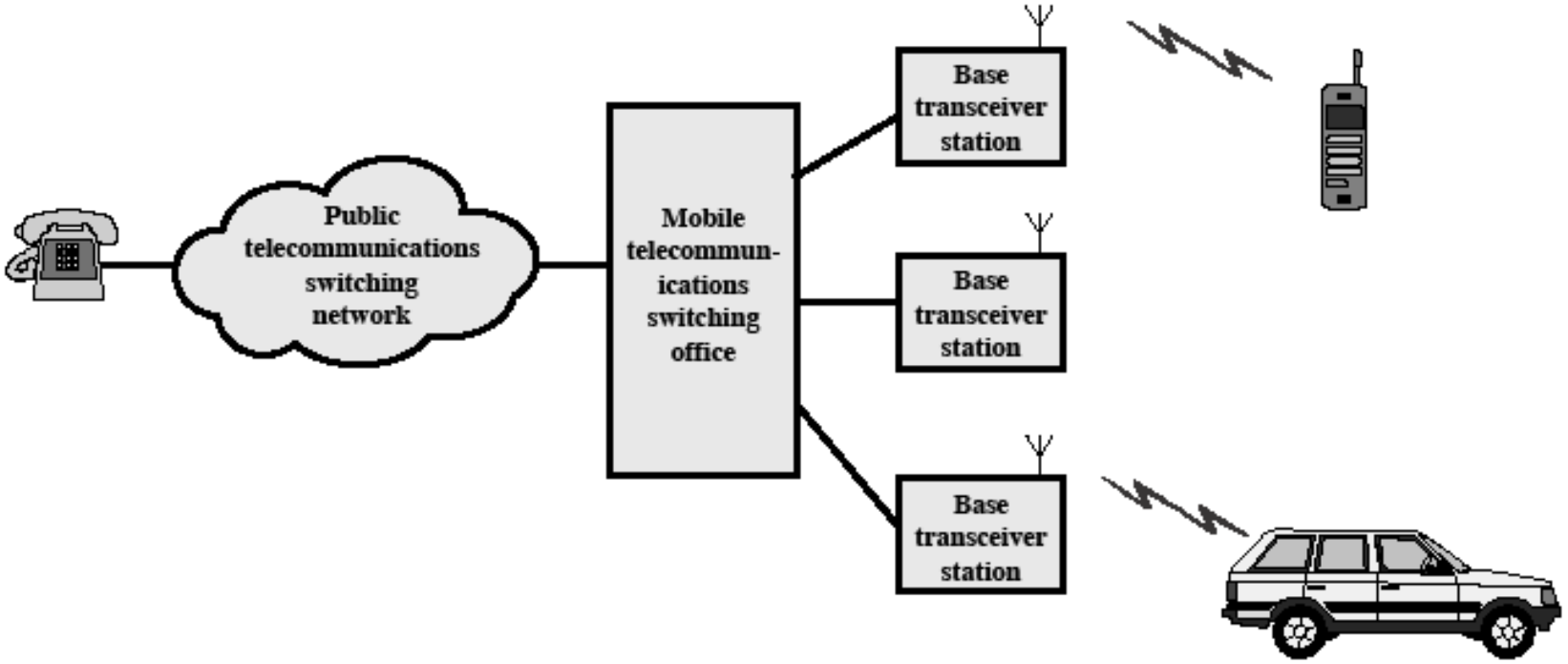
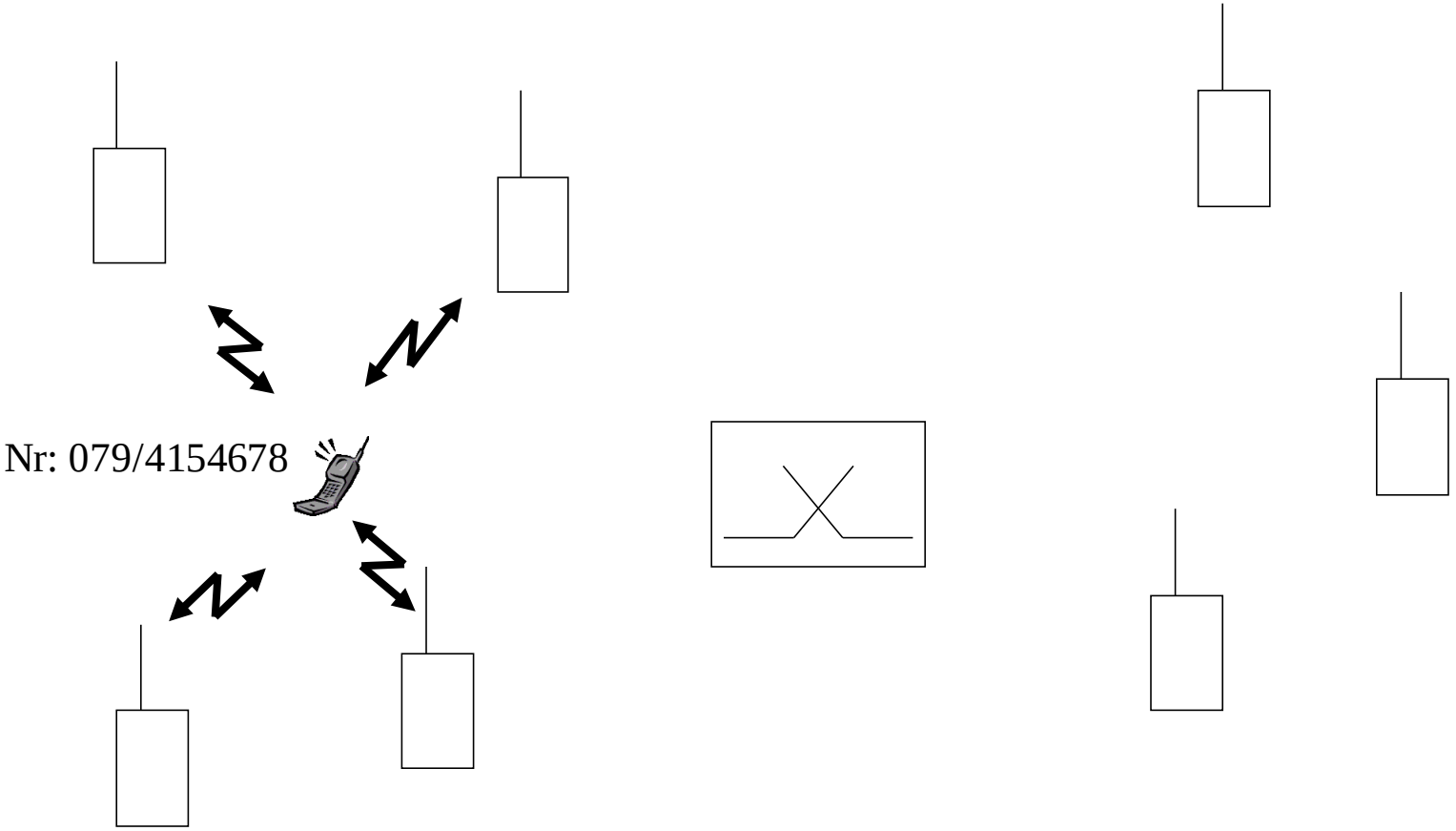


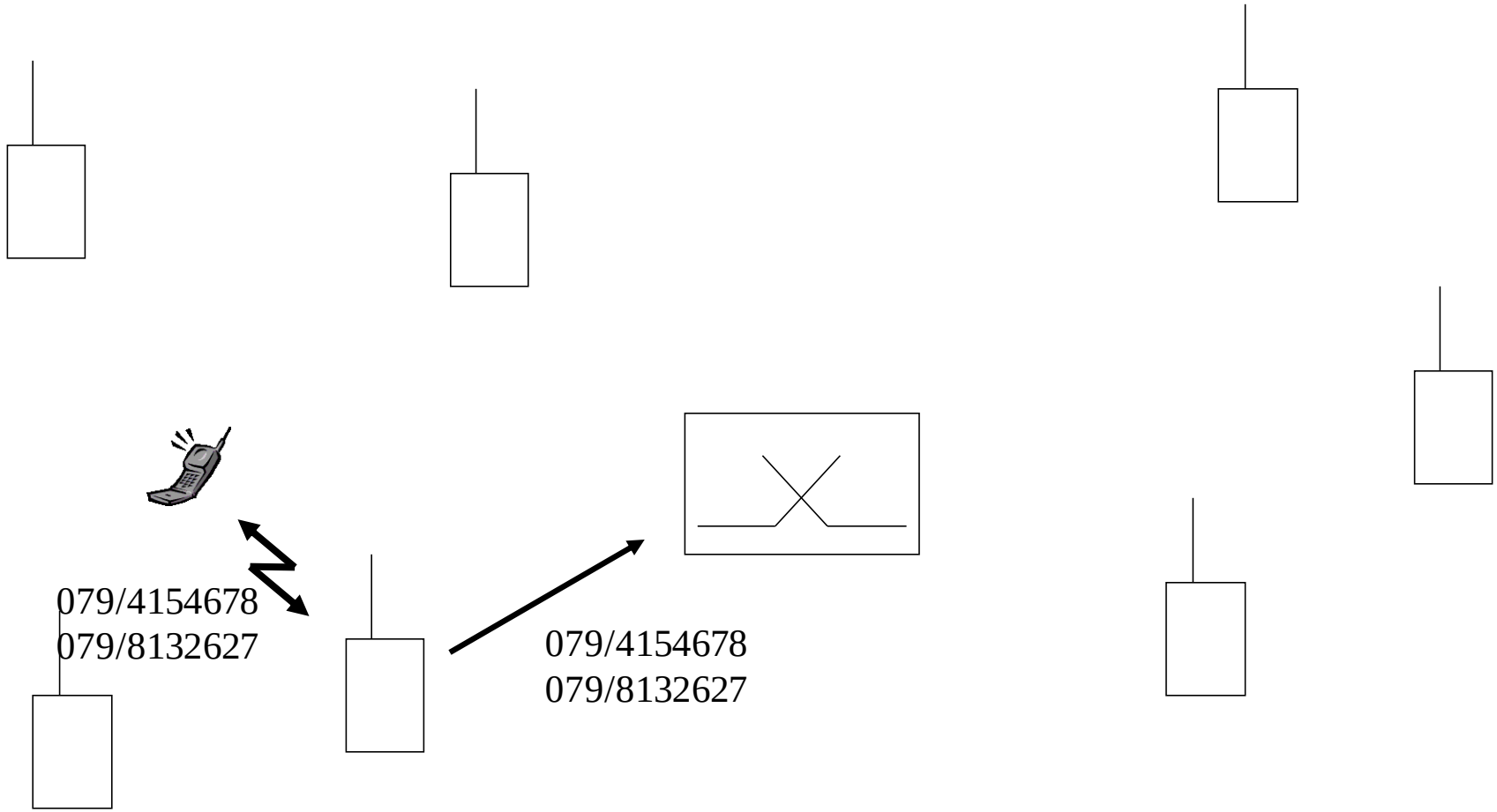
Figure 10.5 Overview of Cellular System

Registration

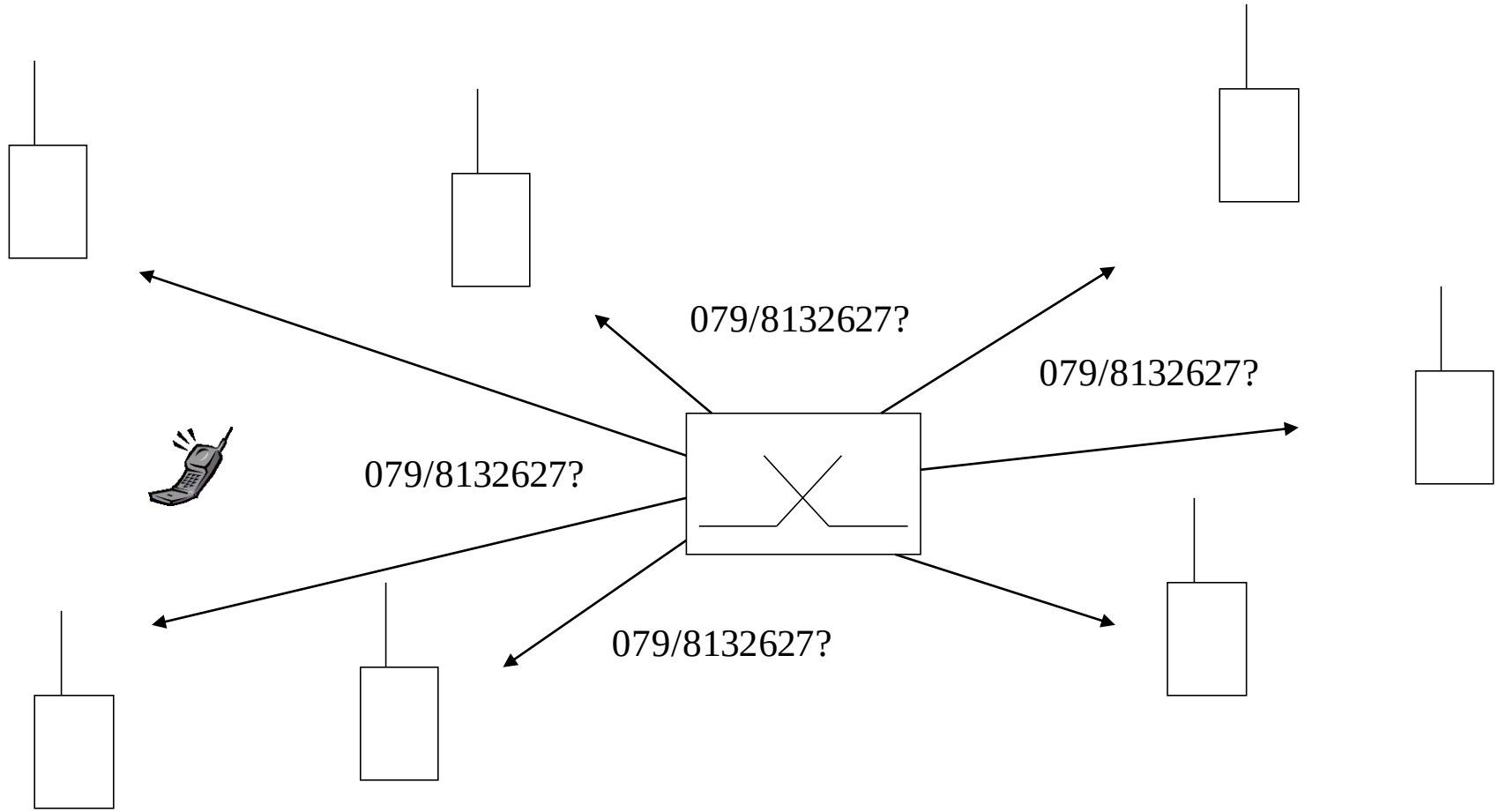


Tune on the strongest signal

Service Request

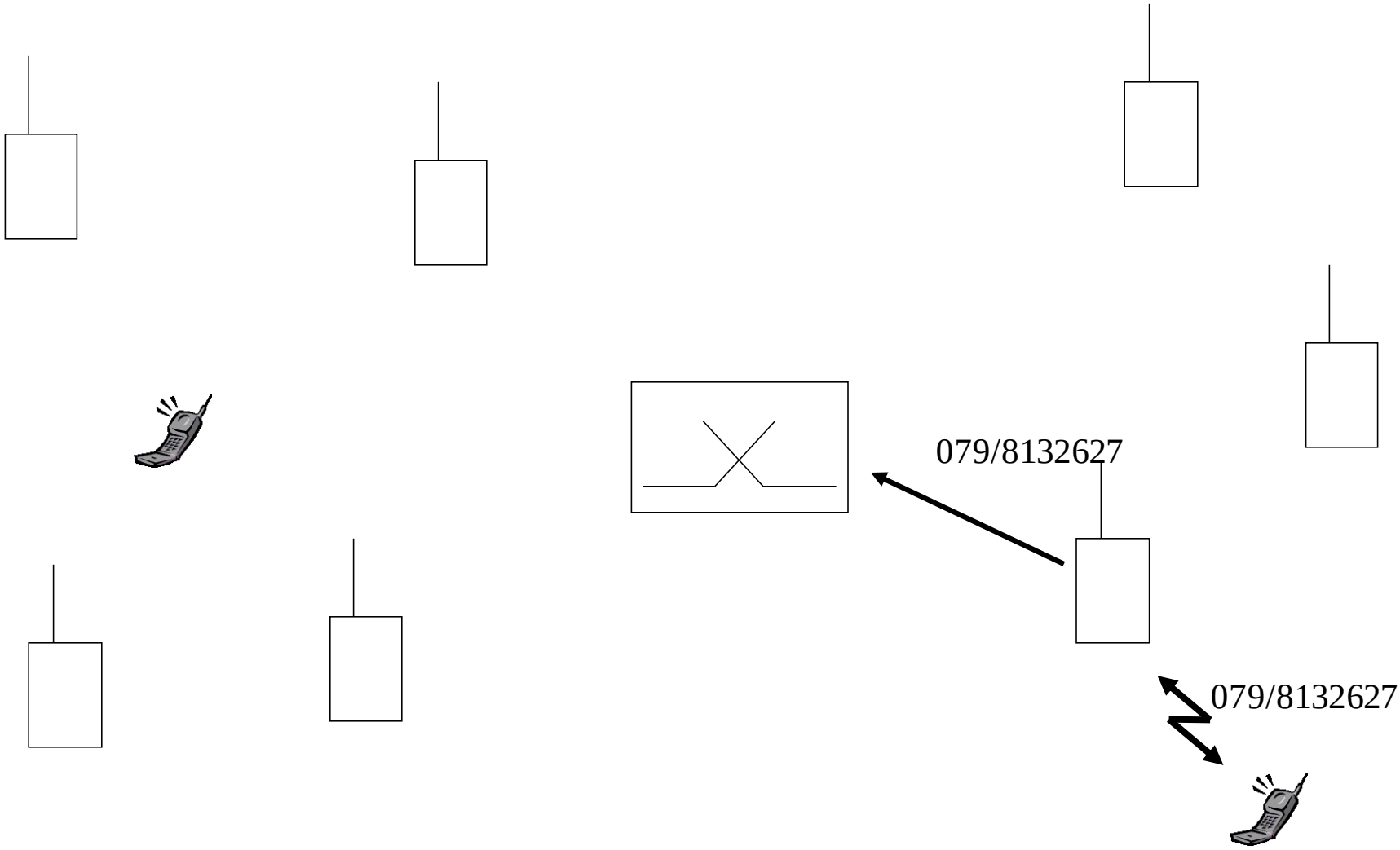


Paging broadcast

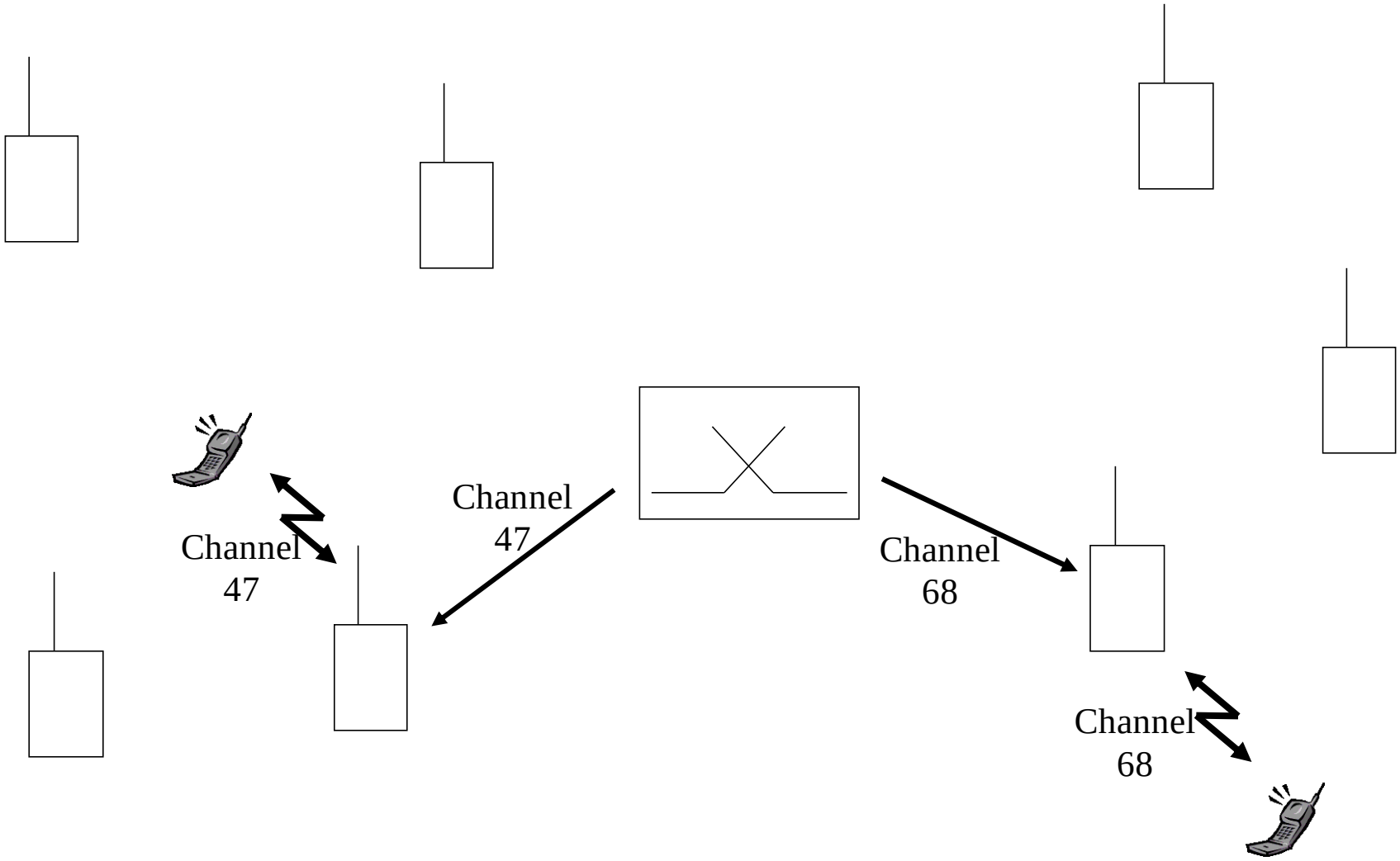


Note: paging makes sense only over a *small* area

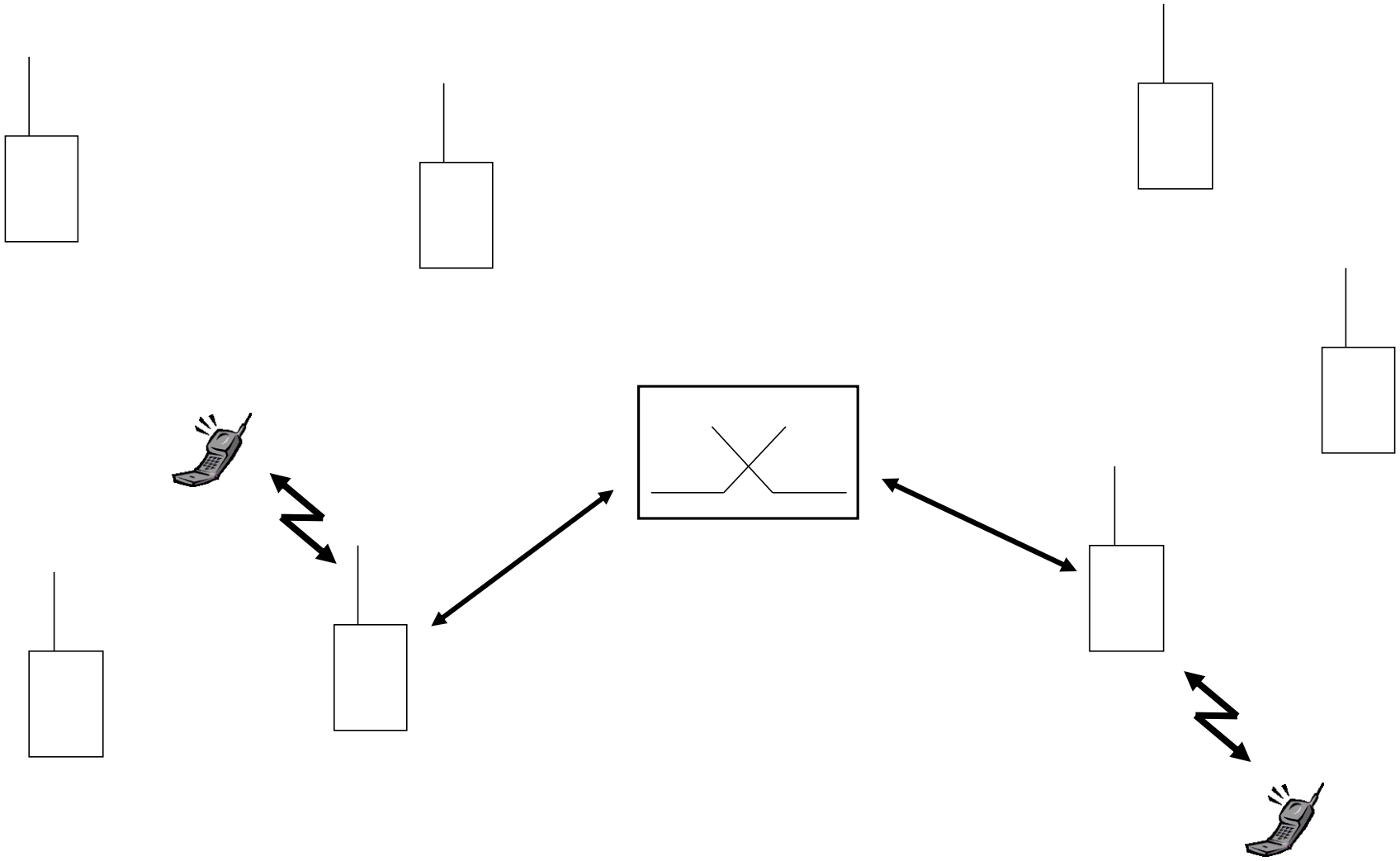
Response



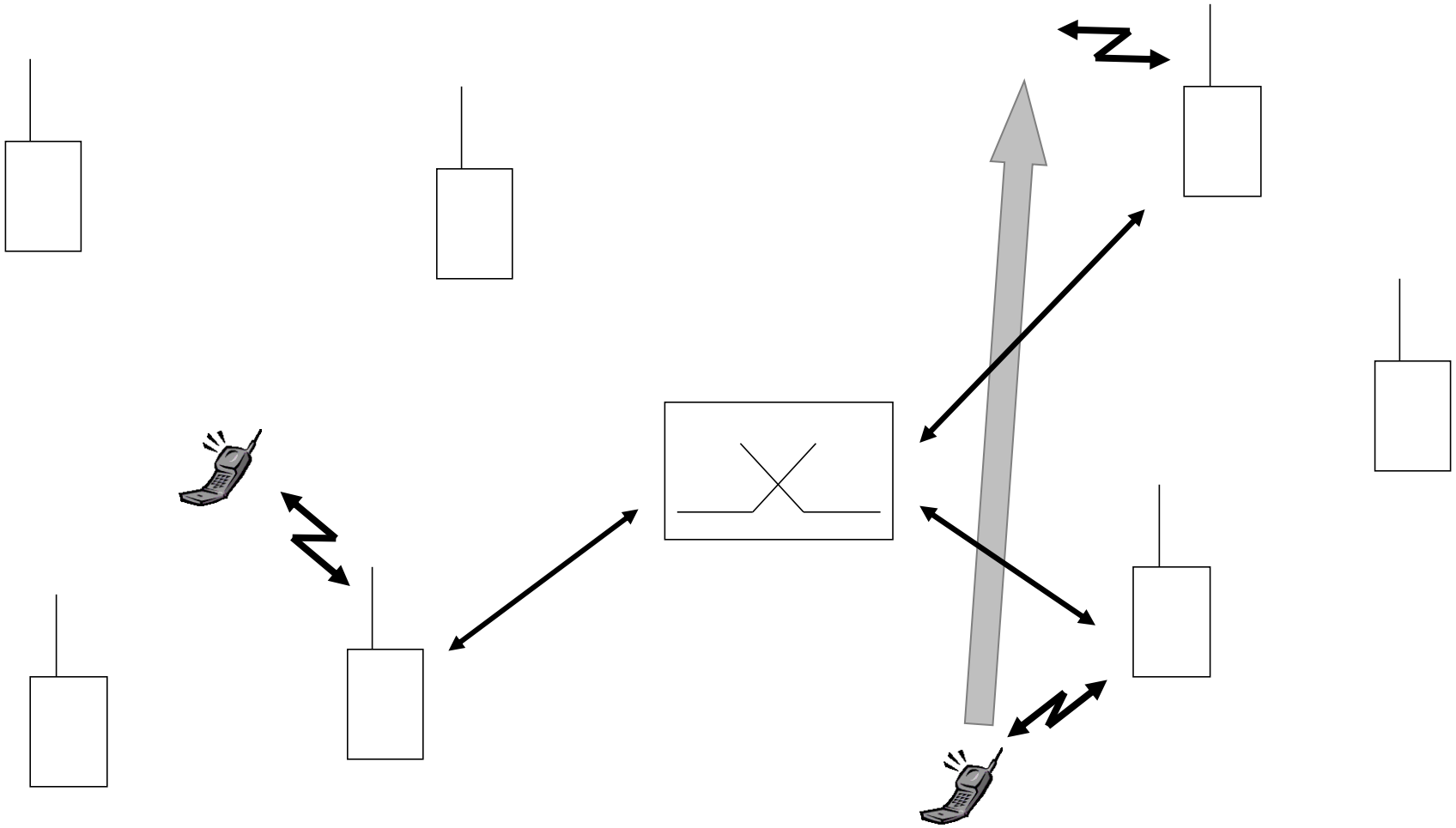
Channel Assignment



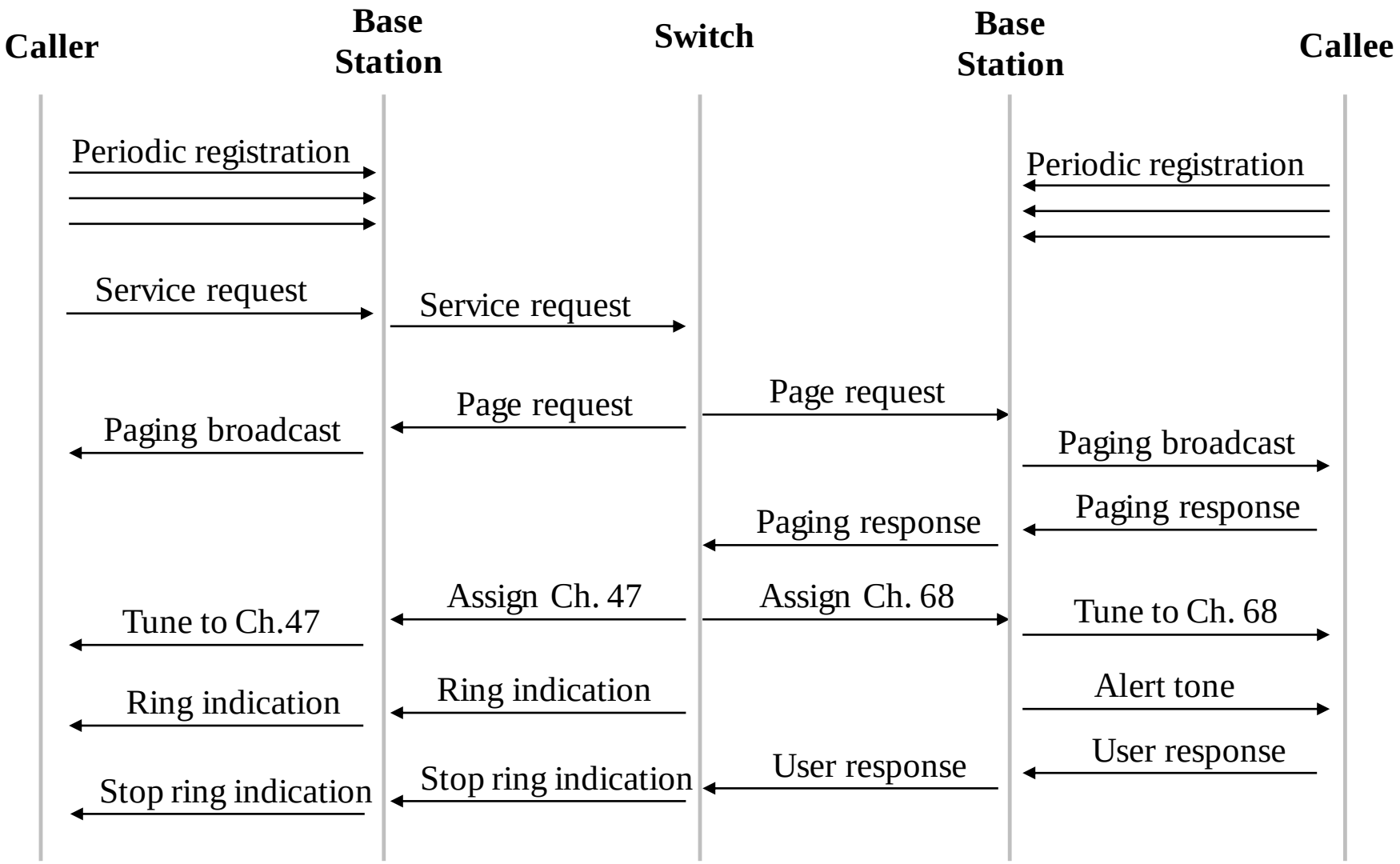
Conversation



Handover (or Handoff)



Message Sequence Chart



Peculiarities of Cellular Networks

- Mobility
  - User location => periodic registration and/or paging
  - Moving from a cell to another => handoff (US) or handover (UK) procedures
  - Moving from one network to another => roaming
- Ether
  - Multiple users per cell => access technology (e.g., SDMA, FDMA, TDMA, CDMA)
  - Channel impairments => coding, error detection, retransmission, forward error correction
  - Bandwidth => channel reuse, signal compression, efficient modulation and coding
  - Privacy and security => encryption
- Energy
  - Limited autonomy => power control, discontinuous transmission

Offered Services

- Telephony services (i.e., voice mail, call transfer,…)
- Short Message Services (SMS)
- Packet switched data (e.g., GPRS, EDGE, HSDPA, LTE), notably for Web access
- Location-based services
- Application store (AppStore of Apple, Application Market of Android,...)
- Entertainment (music, video,…); Mobile TV
- Mobile extension of online social networks (Facebook Mobile,…)
- Friend location (Foursquare, Google Latitude, LocaliserMesAmis,…)
- Peer-to-peer wireless services (e.g., over Bluetooth and WiFi in ad hoc mode);
  NIC (Nokia); FlashLinQ (QualComm)
- …

Relevant Service Features
User Perspective

- Terminal characteristics
  - Weight, size, robustness
  - Price
  - Battery life
  - User interface
- Network characteristics
  - Coverage area (of home network + roaming agreements)
  - Call blocking/dropping
  - Transmission quality (error rate, signal to distortion ratio, delay)
- Service characteristics
  - Price
  - Range of services
  - Confidentiality, Authentication and Privacy

Relevant Service Features

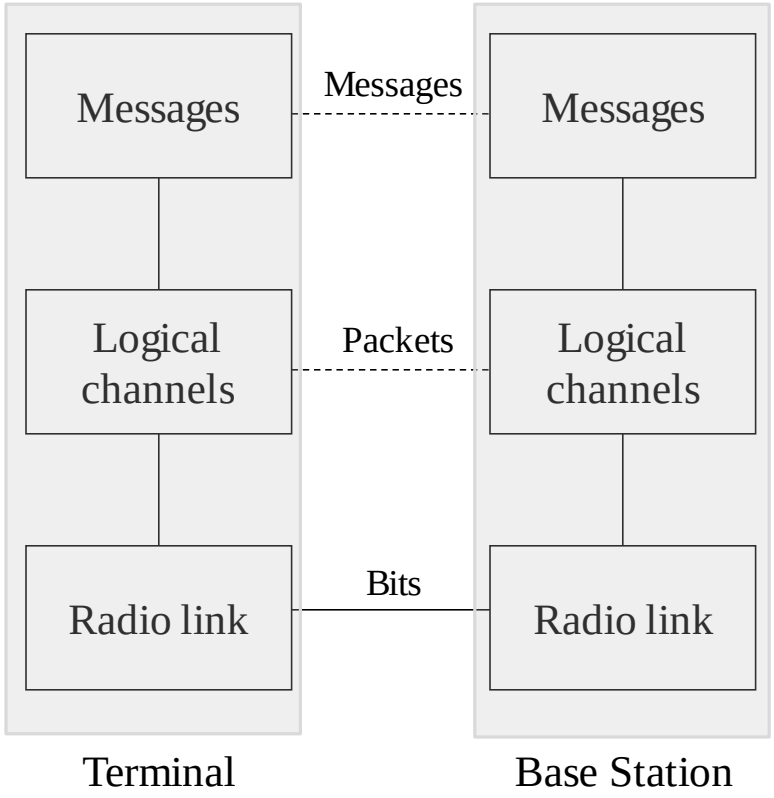
Operator Perspective

- Efficiency
  - Spectrum efficiency
  - Frequency reuse
  - Cell radius
- Cost
  - Infrastructure cost
  - Deployment time and adaptability
  - Roaming agreements
- Security
  - Resistance to fraud
  - Non-repudiability

For telephony:

$$E = \frac{conversations}{cells \times MHz}$$

Air Interface



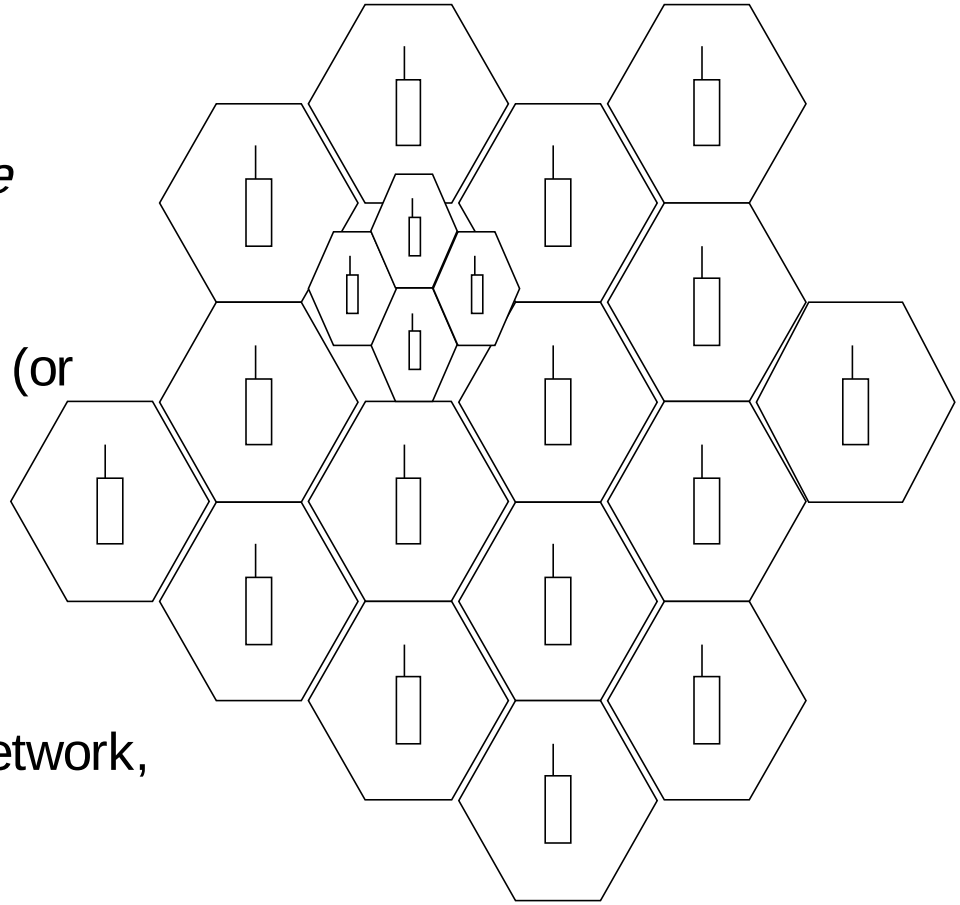
Users' data

Packet structure, error detection/retransmission
Topology: one to one
one to many (e.g., synch signals)
many to one (e.g., service request)

Multiple access (e.g., CDMA, TDMA, FDMA)
Duplex (e.g., Frequency Division Duplex - FDD)
Modulation, source coding, channel coding, interleaving, diversity, channel equalization

Cellular Networks

- Covered area *tesselated* in cells
  - One antenna per cell
  - Cells are controlled by *Mobile Switching Centers*
- A mobile communicates with one (or sometimes two) antennas
- Cells are modeled as hexagons
- Cells interfere with each other
- To increase the capacity of the network, increase the number of cells



Generations of Cellular Networks…

- 1G: analog systems → not in use anymore
- 2G: GSM (introduced in 1992): FDMA/TDMA (900 and 1800MHz)
  - 2.5G: with GPRS: packet switching, extended to E-GPRS (nicknamed EDGE)
- 3G: UMTS (introduced in 2002): CDMA (2100 MHz)
  - 3.5G: with HSPDA (up to 14.4Mb/s); with HSPA+ (up to 84Mb/s)
- 4G: LTE (being introduced in 2013): OFDMA (800 and 2600MHz, then technology neutrality); up to 100Mb/s

GPRS: General Packet Radio Service

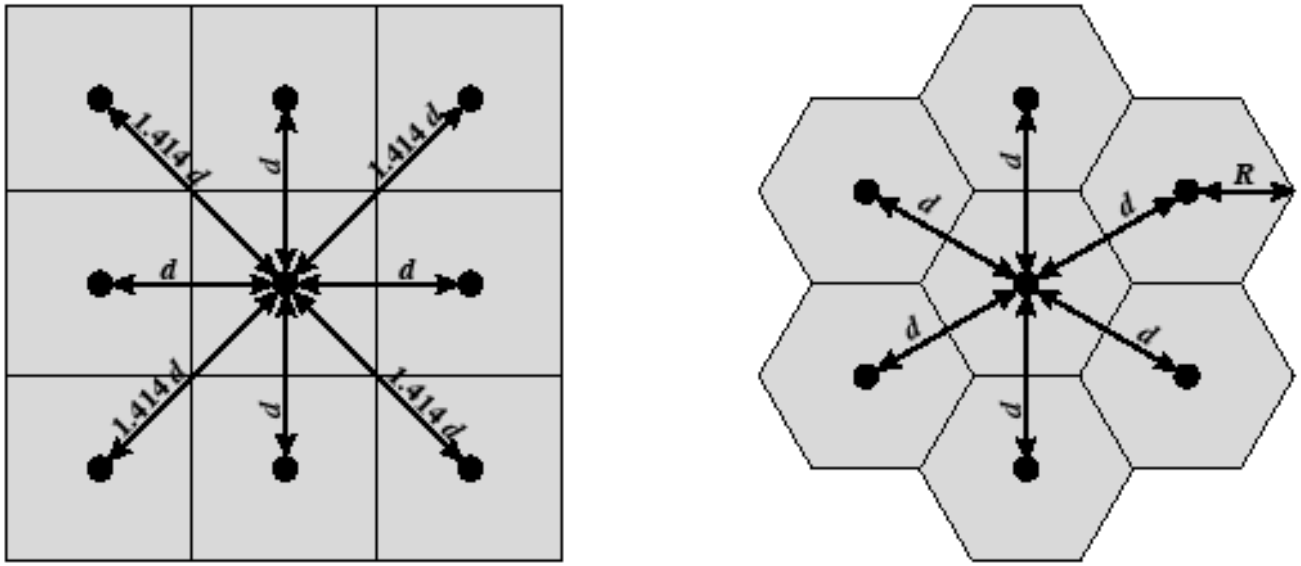
HSPDA: High Speed Downlink Packet Access

LTE: «Long Term Evolution»

For more information: see the 3GPP standards

Area of the hexagon: $1.5R^2\sqrt{3}$

Distance between adjacent cells: $d = \sqrt{3}R$

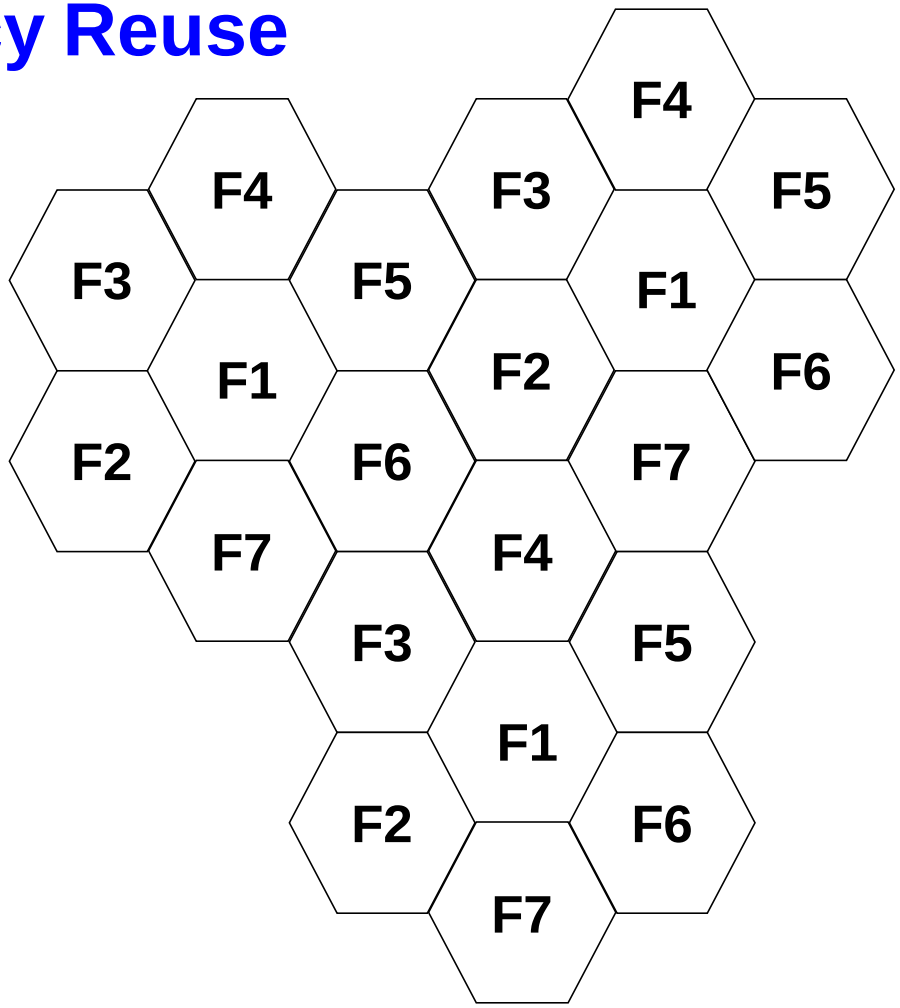


(a) Square pattern

(b) Hexagonal pattern

Figure 10.1 Cellular Geometries

Frequency Reuse

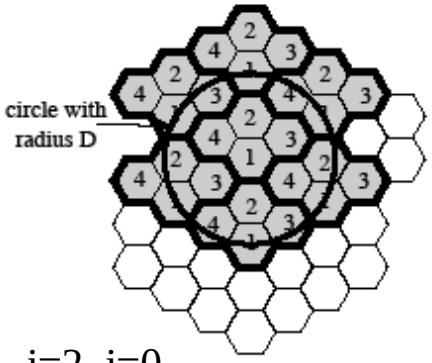


- Cells with the same name use the same set of frequencies
- Cells are organized into clusters
  In this example, the cluster size N = 7
- In order to tesselate, the geometry of hexagons is such that N can only have values which satisfy

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

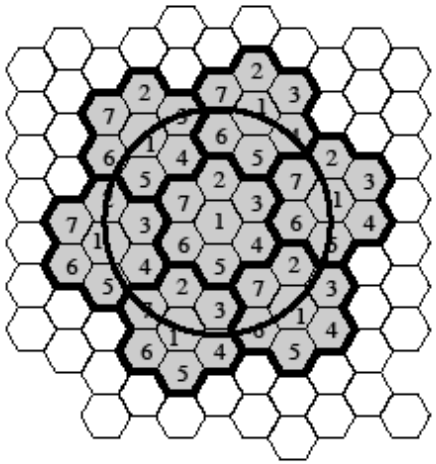
with i = 0,1,2,… and j = 0,1,2,…

- Channel assignment strategies
  - **Fixed:** each cell is allocated a predetermined set of channels
  - **Dynamic:** each time a call request is made, the serving base station requests a channel from the MSC



i=2, j=0

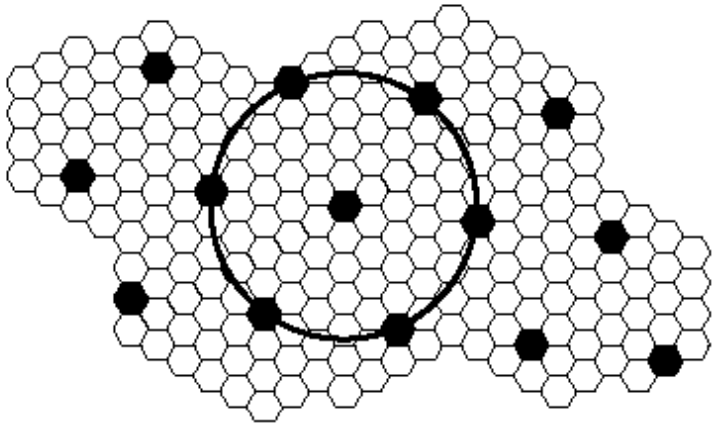
(a) Frequency reuse pattern for $N = 4$



i=2, j=1

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

N: cluster size



i=3, j=2

(c) Black cells indicate a frequency reuse for $N = 19$

Figure 10.2 Frequency Reuse Patterns

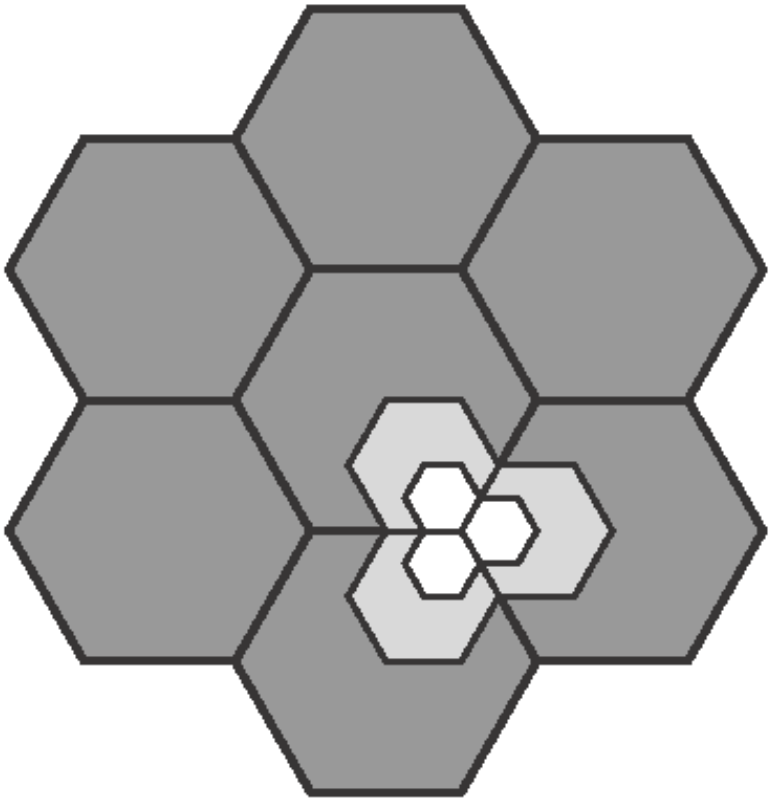


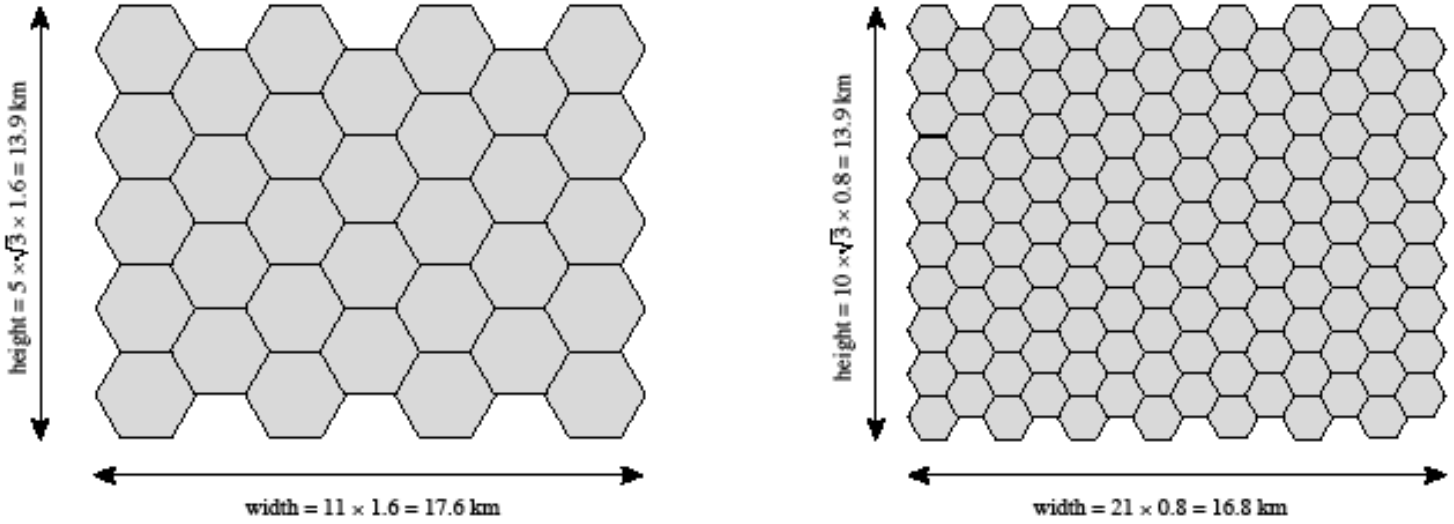
Figure 10.3 Cell Splitting

Example: system of 32 cells with cell radius of 1.6km
Total frequency bandwidth supporting 336 traffic channels
Reuse factor (or cluster size) = 7
What geographic area is covered?
Total number of supported channels?

Solution:
Cell area = 6.65km2
Covered area: 32*6.65=213km2
Channels/cell = 336/7=48
Total channel capacity: 32*48=1536 channels

Same question for a system of 128 cells with cell radius of 0.8km. As before:
- total frequency bandwidth supporting 336 traffic channels
- reuse factor (or cluster size) = 7

Solution:
Cell area: 1.66km2
Covered area: 128*1.66=213km2
Total channel capacity: 128*48=6144



(a) Cell radius = 1.6 km

(b) Cell radius = 0.8 km

Figure 10.4 Frequency Reuse Example

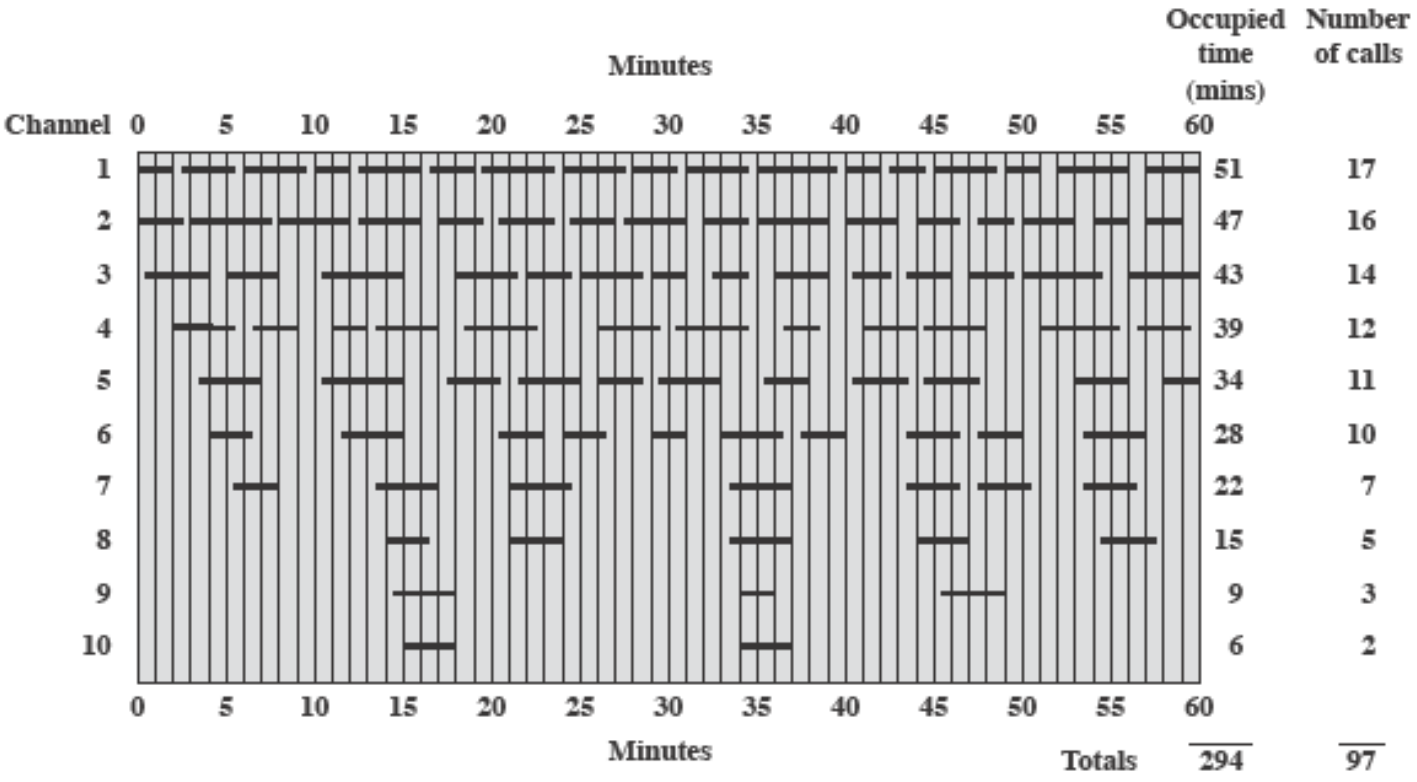


Figure 10.8 Example Distribution of Traffic in a Cell with Capacity 10

Rate of calls per minute: 97/60
Average holding time per call: 294/97

Offered traffic: 294/60 = 4.9 Erlangs

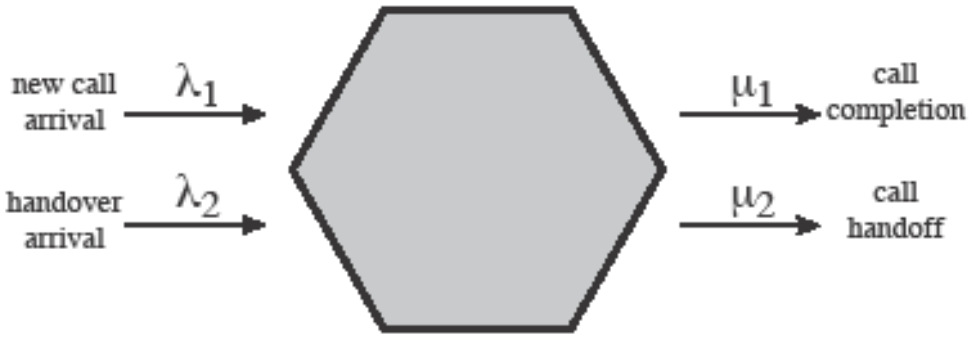


Figure 10.9 Cell Traffic Model

Interference & System Capacity

- Sources of interference
  - **Co-channel** interference (same frequency)
    - A call in a neighboring cell
    - Other base stations operating in the same frequency band
    - Non-cellular system leaking energy into the frequency band
  - **Adjacent channel** interference (adjacent frequency)
    - Another mobile in the same cell

- Consequences of interference
  - On data channel:
    - Crosstalk (voice)
    - Erroneous data (data transmission)
  - On control channel:
    - Missed/dropped calls

Decibels (reminder)

- The decibel is a dimensionless unit used to express a power ratio

$$B = 10 \cdot \log_{10}\left(\frac{P}{P_0}\right)$$

where P_0 is the reference power level and P is the considered power level

- Decibel (dB)
  - express the magnitude of a physical quantity relative to a reference level.
  - represent very large range of ratios
  - are easy to manipulate (e.g., consecutive amplifiers)

- A ratio
  - can be expressed in decibels relative to 1 Watt (dBW)
  - is more frequently expressed in decibels relative to 1mW (dBm)

$$P = 10 \cdot \log_{10}\left(\frac{P}{1mW}\right)$$

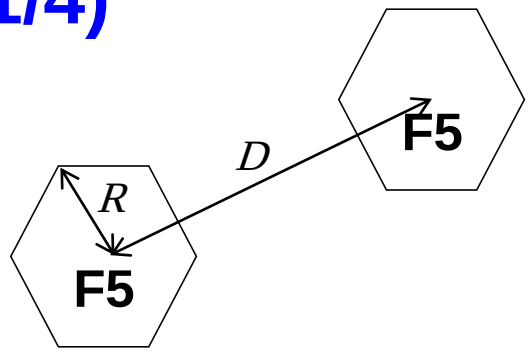
Example:
If the transmission power P_0 is 10W and the received power P is 0.1W, the loss is

$$10\log_{10}\left(\frac{1}{100}\right) = -20dB$$

Co-channel Interference (1/4)

- **Co-channel reuse ratio Q**

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



where D = distance to the center of the nearest co-channel cell
R = radius of a cell
N = cluster size (or "reuse factor")

- **Signal-to-interference ratio (SIR)**

$$SIR = \frac{S}{I} = \frac{S}{\sum_{i=1}^{i_0} I_i}$$

where S = desired signal power
I_i = interference power caused by the ith interfering co-channel base station
i_0 = number of co-channel interfering cells

- **Average received power P_r** at a distance d from the transmitting antenna

$$P_r = P_0 \left(\frac{d}{d_0} \right)^{-\alpha} \quad \text{or} \quad P_r(\text{dBm}) = P_0(\text{dBm}) - 10\alpha \log \left(\frac{d}{d_0} \right)$$

where P_0 = power received at a small distance d0 from the transmitting antenna
α = path loss exponent

Co-channel Interference (2/4)

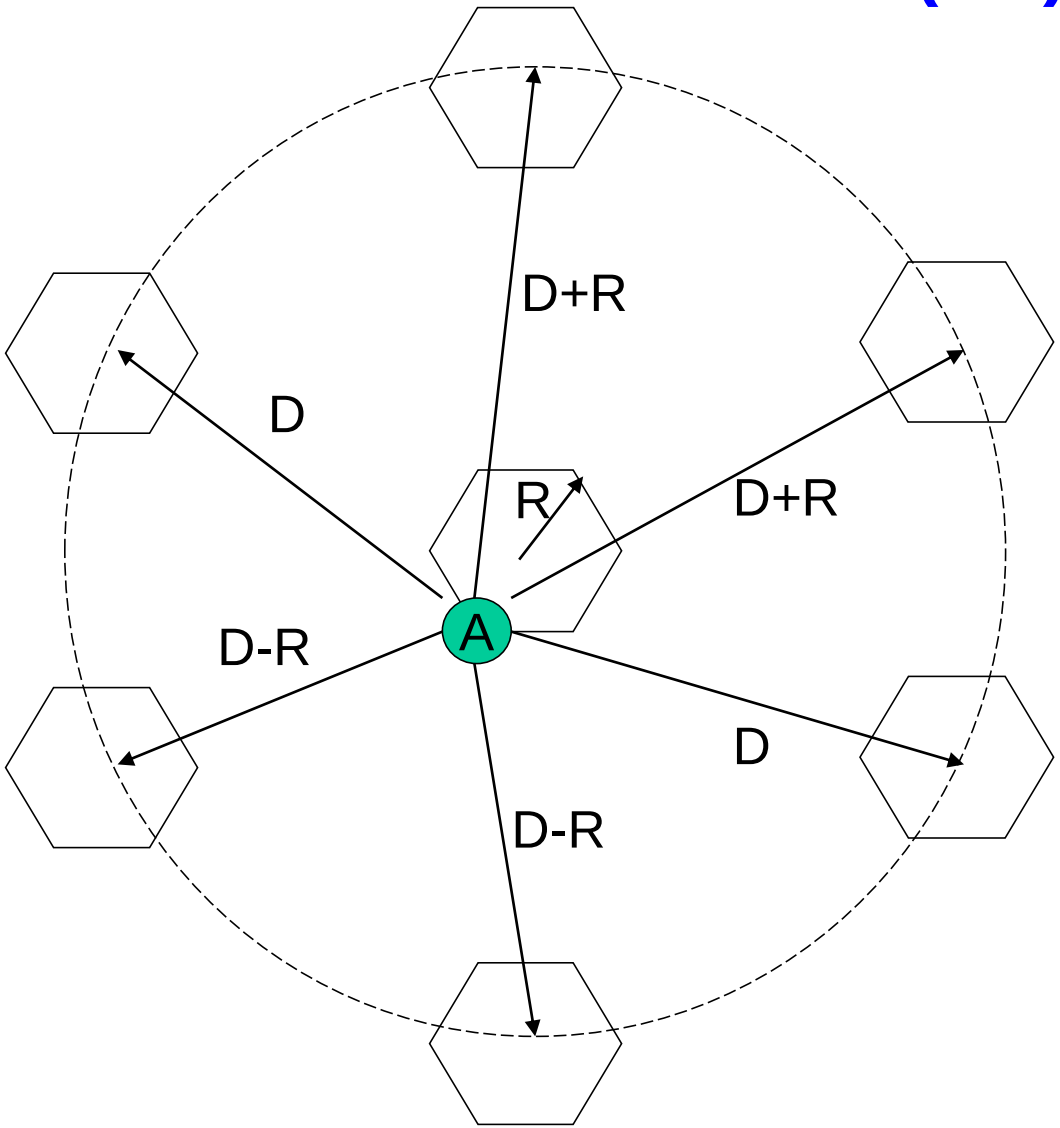
If the transmit power of each base station is equal and α is the same throughout the coverage area, in a corner of a cell (most remote place from the base station in the cell) we have:

$$\frac{S}{I} = \frac{R^{-\alpha}}{\sum_{i=1}^{i_0} D_i^{-\alpha}}$$

Considering only the first layer of interfering cells and assuming that they are equidistant from the desired base station (all at distance D):

$$\frac{S}{I} = \frac{(D/R)^{\alpha}}{i_0} = \frac{\left(\sqrt{3N}\right)^{\alpha}}{i_0}$$

Co-channel Interference (3/4)



First tier of co-channel cells for a cluster size of N=7
Note: the marked distances are approximations

Co-channel Interference (4/4)

Approximation of the SIR at point A

$$\frac{S}{I} = \frac{R^{-\alpha}}{2(D-R)^{-\alpha} + 2D^{-\alpha} + 2(D+R)^{-\alpha}}$$

Using the co-channel ratio

$$\frac{S}{I} = \frac{1}{2(Q-1)^{-\alpha} + 2Q^{-\alpha} + 2(Q+1)^{-\alpha}}$$

Numerical example: If N=7, alpha = 4, then Q~4.6 and

$$\frac{S}{I} \approx 49.56 \approx 17.8\ dB$$

Capacity of Cellular Networks (1/2)

FDMA/TDMA

- FDMA/TDMA capacity is *bandwidth limited*

- Consider the downlink channel interference. Assume that the mobile is located at the edge of the cell. Consider only the interference from the first tier of co-channel cells (6 cells if N = 7).

We want the SIR to be greater than a given minimum SIR_{min}

$$\frac{S}{I} = \frac{R^{-\alpha}}{\sum_{i=1}^{i_0} D_i^{-\alpha}} = \frac{1}{6}\left(\frac{R}{D}\right)^{-\alpha} \geq \left(\frac{S}{I}\right)_{\min}$$

Using the co-channel reuse ratio $Q = \sqrt{3N}$ and because *Q=D/R*:

$$Q = \left(6\left(\frac{S}{I}\right)_{\min}\right)^{1/\alpha}$$

Capacity of Cellular Networks (2/2)

FDMA/TDMA

Radio capacity of cellular network

$$m = \frac{B_t}{B_c N} \quad \text{radio channels/cell}$$

where B_t is the total allocated spectrum for the system
B_c is the channel bandwidth

Using the co-channel reuse ratio

$$m = \frac{B_t}{B_c \frac{Q^2}{3}} = \frac{B_t}{B_c \left(\frac{6}{3^{\alpha/2}} \left(\frac{S}{I} \right)_{\min} \right)^{2/\alpha}}$$

Techniques to improve capacity
- Cell splitting
- Sectoring

Capacity of Cellular Networks

CDMA

- CDMA capacity is *interference limited*
- Techniques to reduce interference
  - Multi-sectorized antennas
  - Discontinuous transmission mode (takes advantage of intermittent nature of speech); duty factor between 3/8 and ½.
- **Power control:** for a single cell, all uplink signals should be received approximately with the same power at the base station
- **Pilot signal:** transmitted by the base station; used by each mobile to set its own power (for the uplink)

CDMA Capacity: single cell case (1/2)

Let N = number of users

S = power of the signal received at the base station from a single user

$$SNR = \frac{S}{(N-1)S} = \frac{1}{N-1}$$

Bit energy to noise ratio

$$\frac{E_b}{N_0} = \frac{S/R}{(N-1)(S/W)} = \frac{W/R}{N-1}$$

where R = bitrate

W = available bandwidth

N_0 = noise spectral density

Taking the thermal noise η into account

$$\frac{E_b}{N_0} = \frac{W/R}{(N-1)+(\eta/S)}$$

Thus, the number of users that can access the system is

$$N = 1 + \frac{W/R}{E_b/N_0} - (\eta/S)$$

CDMA Capacity: single cell case (2/2)

To increase this number, 2 main techniques:

- Leverage on the sporadicity of users' activity (e.g., switch off a user while he does not talk)
- Antenna sectorization

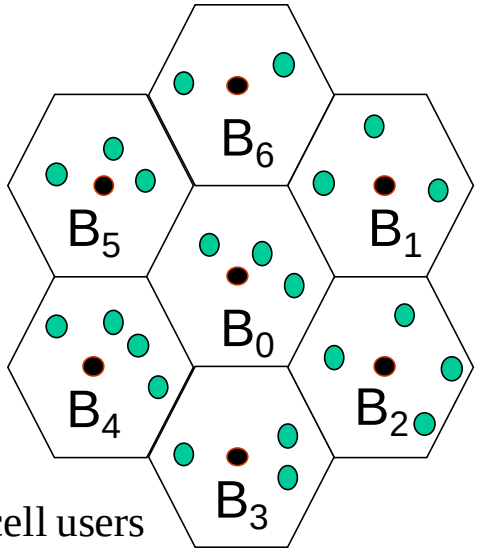
Let δ = duty cycle (or factor) of voice (typically between 3/8 and ½)
N_s = number of users **per sector**

$$\frac{E_b}{N_0} = \frac{W/R}{(N_s - 1)\delta + (\eta / S)}$$

If the number of users is large and thermal noise is neglected:

$$N_s = 1 + \frac{1}{\delta}\left[\frac{W/R}{E_b/N_0}\right]$$

CDMA Capacity: multiple cells case (1/3)



B_0 controls the transmit power of its in-cell users, but not that of users in neighboring cells

Frequency reuse factor on the uplink

$$f = \frac{N_0}{N_0 + \sum_i U_i N_{ai}}$$

where N_0 = total interference power received from N-1 in-cell users
U_i = number of users in the ith adjacent cell
N_{ai} = average interference power from a user located in the ith adjacent cell

Average received power from users in adjacent cell is computed as

$$N_{ai} = \sum_j N_{ij} / U_i$$

where Nij = power received at the base station of interest from the jth user in the ith cell

CDMA Capacity: multiple cells case (2/3)

Concentric circular geometry

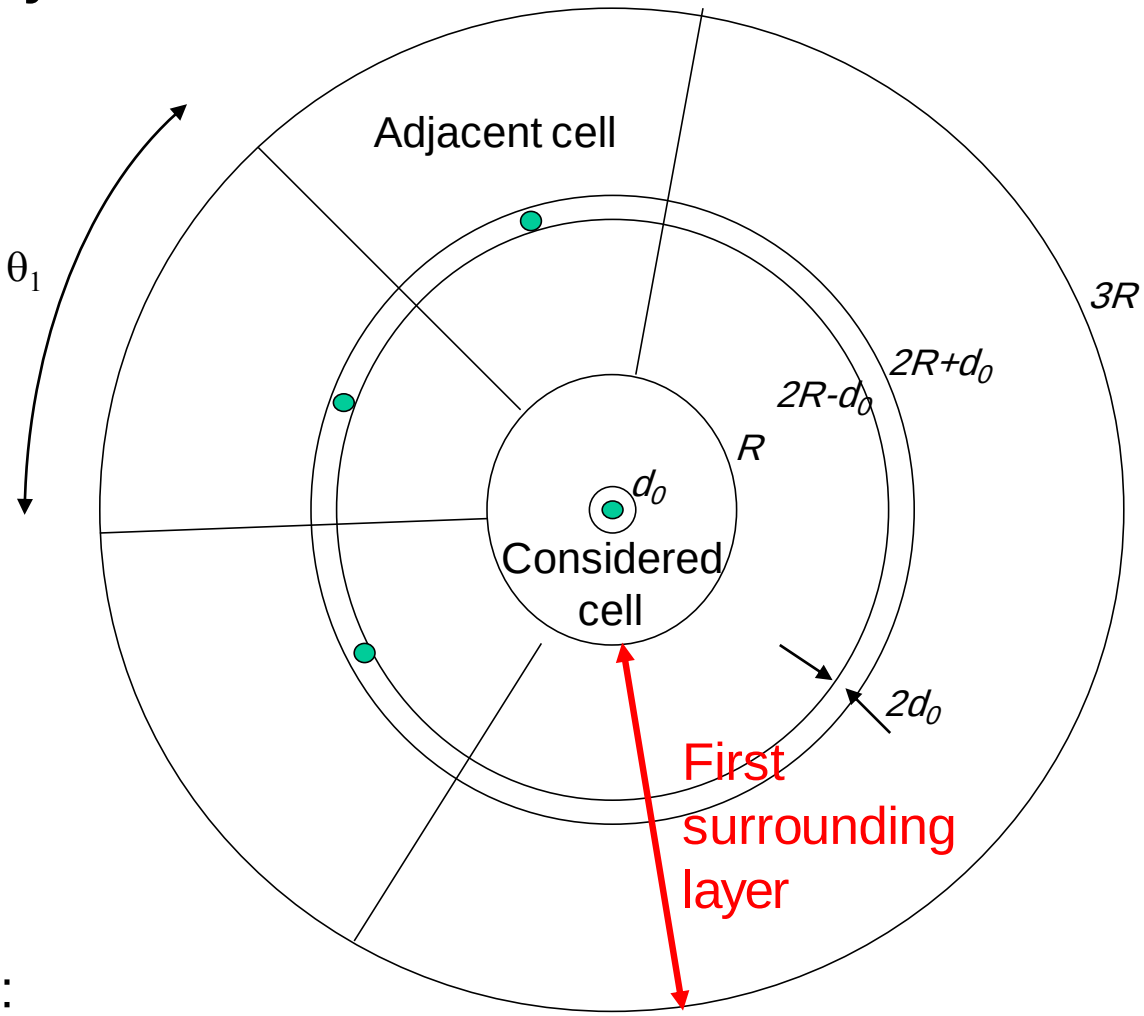
M_1 : number of wedge-shaped cells of the first surrounding layer of cells

A_1 : area of the first surrounding layer

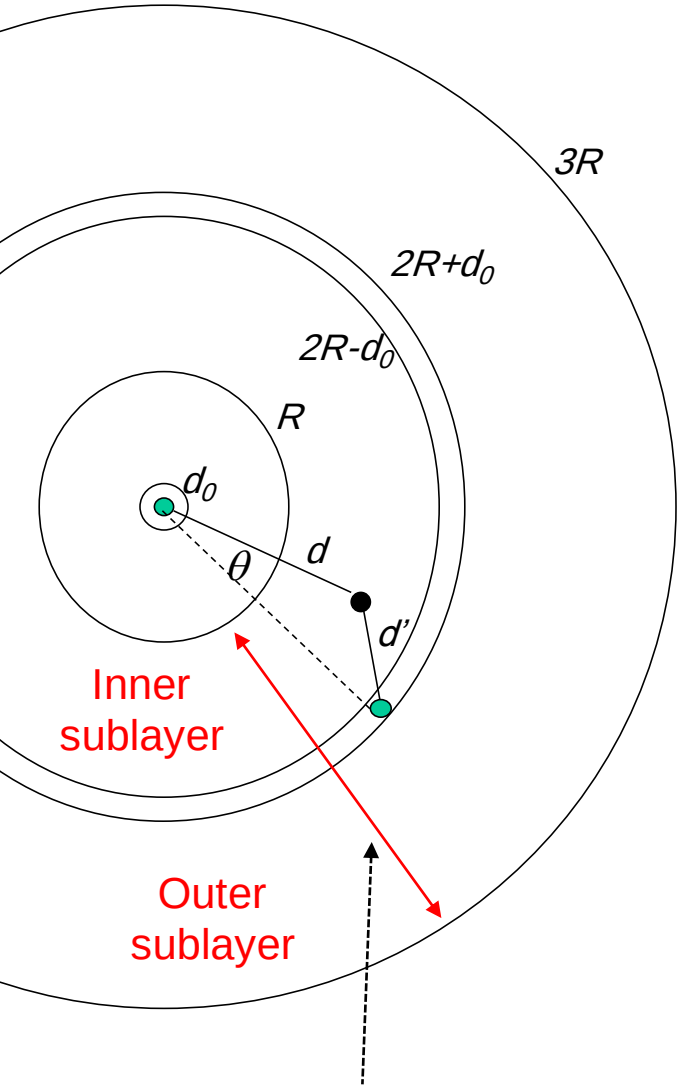
$A_1 = M_1 A$

To let all cells have the same size A, we must have:
$M_1 = 8$
$\theta_1 = 45^0$

By recursion, for the ith layer:
$A_i = i8A$
$\theta_i = \pi/4i$



CDMA Capacity: multiple cells case (3/3)



For the inner sublayer, namely for $(2i-1)R \le d \le (2i)R - d_0$ (case depicted in the figure):

$$d' = \sqrt{d^2 \sin^2\theta + \left(2Ri - d_0 - d\cos\theta\right)^2}$$

For the outer sublayer, namely for $(2i)R + d_0 \le d \le (2i+1)R$:

$$d' = \sqrt{d^2 \sin^2\theta + \left(d\cos\theta - 2Ri - d_0\right)^2}$$

Interference power at B_0 from the *j*th subscriber of the *i*th cell:

$$P_{0,i,j}(r,\theta,d_0) = P_0(d'/d_0)^{\alpha}(d_0/d)^{\alpha}$$

In practice, the frequency reuse efficiency f for CDMA is in the order of 0.3 to 0.7 (as a comparison, in the case of FDMA with cluster size = 7, f = 1/7).

Note: i is the layer number (i=1 if we consider only the first layer)

Conclusion

- In this Module D2, we have addressed essentially network capacity
- Cellular networks: many base stations
- Capacity can be increased notably by cell splitting and cell sectoring
- Reminder: Frequency division technique used in cellular network generations (all with SDMA, of course):
  - 2G: GSM: FDMA/TDMA
  - 3G: UMTS: CDMA
  - 4G: LTE: OFDMA (Orthogonal Frequency-Division Multiple Access) for the downlink and SC-FDMA (Single-carrier Frequency Division Multiple Access) for the uplink

References

- Agrawal & Zeng: Chapter 5
- T. Rappaport: Wireless Communications, 2nd edition, Prentice Hall, 2001
- M. Schwartz: Mobile Wireless Communications, Cambridge University Press, 2005
- W. Stallings: Wireless Communications and Networks, 2nd edition, Prentice Hall, 2005, Chapter 10
- Schiller, Chapter 4