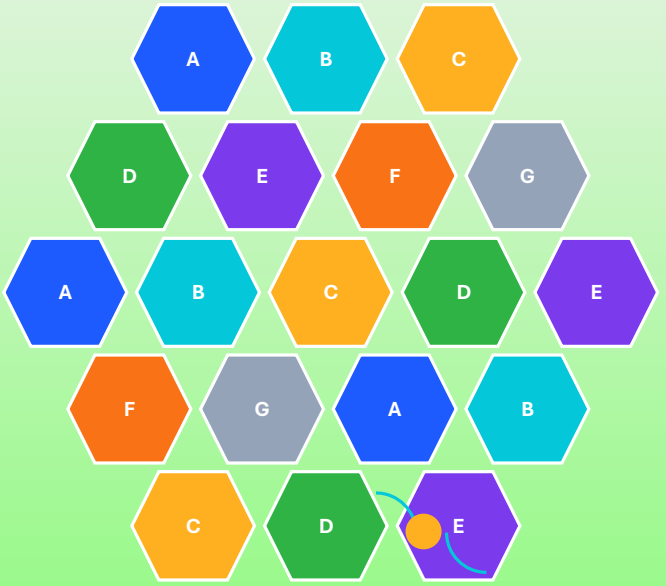
Cellular System

Cellular network design, capacity, interference and handoff



Learning roadmap

OVERVIEW

What you should be able to explain and calculate after this lecture

1

Wireless basics

system elements, channels and duplexing

2

Cellular concept

cells, clusters, footprints and reuse pattern

3

Frequency reuse

reuse factor, cluster size and reuse distance

4

Capacity planning

channel count, blocking, interference trade-offs

5

Mobility + expansion

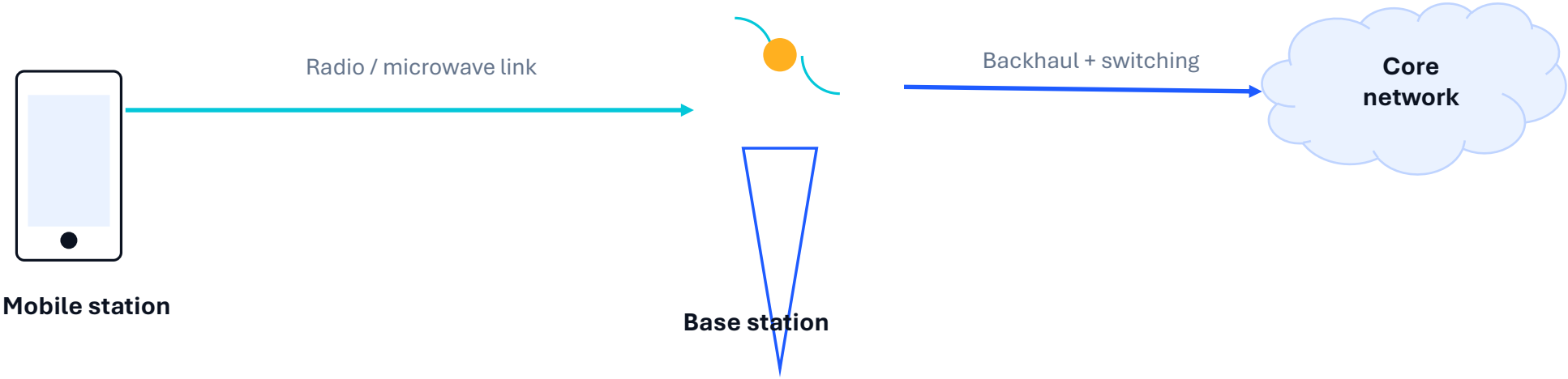
handoff, umbrella cells, splitting and sectorization

Main theme: reuse the same scarce spectrum many times — but keep co-channel cells far enough apart so interference remains tolerable.

Wireless communication: the basic idea

FOUNDATION

Information travels by electromagnetic waves instead of physical wires



Wireless networking replaces copper/fiber in the access path with radio waves. The design challenge is to share limited spectrum while serving moving users.

Key elements in a cellular system

DEFINITIONS

Know the role of each network component

Mobile station

User device operating while moving or at unspecified locations.

Base station

Fixed radio site serving a coverage region with antennas and channels.

MSC / MTSO

Switching center coordinating call routing between cells and PSTN.

Subscriber

User who pays for and accesses the mobile service.

Transceiver

Device capable of transmitting and receiving radio signals.

Tip: cellular networks are not only radio towers. The core network, switching, authentication and billing systems also determine service quality.

Channels and duplexing

RADIO LINKS

Different logical channels support setup, downlink and uplink communication

Control channel

- Call setup
- Call request
- Beacon and control signaling

Forward channel

- Base station → mobile
- Downlink user information

Reverse channel

- Mobile → base station
- Uplink user information

Simplex / Half duplex

- Simplex: one-way only
- Half duplex: two-way, but one direction at a time
- Example: walkie-talkie

Full duplex

- Two-way simultaneously
- Typically uses paired channels in FDD
- Example: telephone call

Cellular concept

Divide a large service area into many smaller cells

CELLULAR IDEA

- A cell is the basic geographic unit of coverage.
- Each cell is served by one base station and a group of channels.
- Hexagons are used in planning because they tile an area without gaps and approximate circular radio coverage.
- Neighboring cells use different channel groups to limit interference.

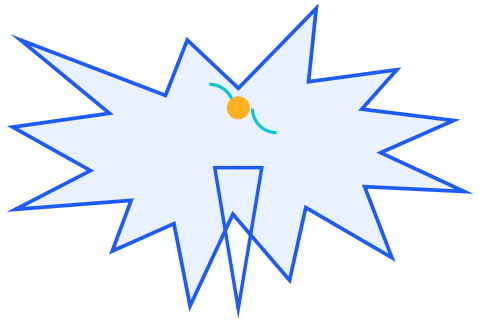
capacity ↑ by frequency reuse

Cells, footprints and clusters

PLANNING UNITS

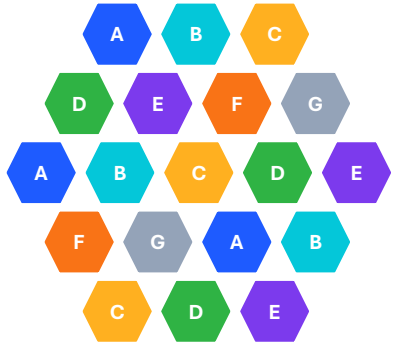
Planning uses ideal hexagons; real radio coverage is less regular

Cell footprint



- Actual radio coverage depends on terrain, buildings, antenna height and transmit power.
- Systematic planning approximates cells with regular shapes.

Cluster



- A group of cells in which no channel group is repeated.
- The whole cluster is replicated across the service area.

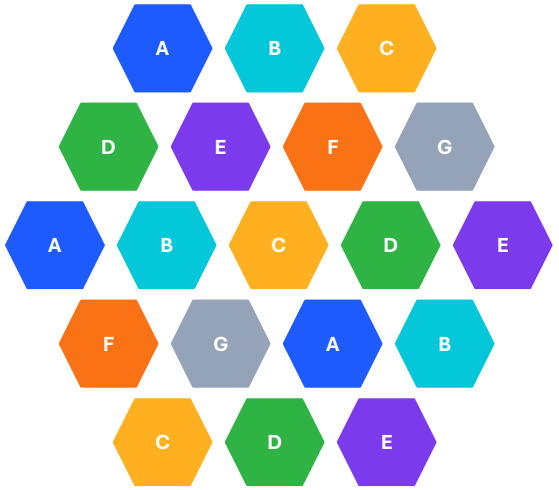
Design rule

- Adjacent cells should not use the same frequencies.
- Reuse cells must be separated enough to keep co-channel interference under control.

Frequency reuse: the core concept

REUSE

Reuse the same channel set in non-adjacent cells



Cluster A–G repeated across geography

What reuse achieves

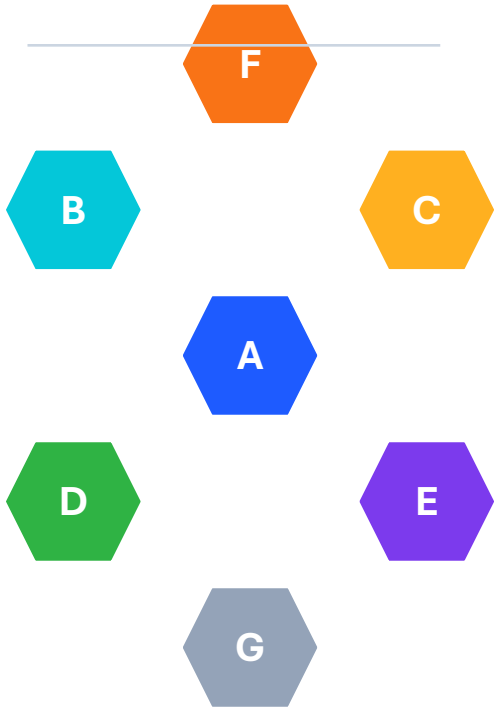
- The cellular network is split into small cells.
- Each cell receives a set of frequencies.
- Same frequency bands are reused in distant cells.
- Spectrum efficiency rises because limited bandwidth serves more users.

Key point: frequency reuse is not “using the same frequency everywhere”; it is planned repetition with distance.

A 7-cell reuse pattern

PATTERN

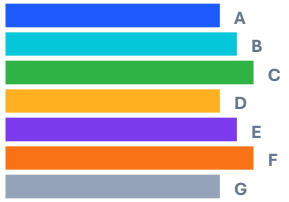
Seven channel groups are assigned, then the pattern repeats



Cluster size N = 7

Interpretation

- A–G represent different channel groups.
- No two adjacent cells share the same group.
- After one cluster, the same group can appear again at a reuse distance D.



Frequency reuse factor

FORMULA

How much of the total spectrum is available to one cell?

$$\text{reuse factor} = 1 / N$$

- N = number of cells in one cluster.
- If N is large, each cell receives a smaller portion of the total spectrum, but interference is lower.
- If N is small, capacity per area is higher, but co-channel interference is higher.

$$N = i^2 + i \cdot j + j^2$$

- Only certain cluster sizes fit perfectly on a hexagonal grid.
- i and j are non-negative integers describing movement across hexagons to the nearest co-channel cell.

Common cluster sizes: N = 3, 4, 7, 9, 12, 19, 21. Legacy cellular planning frequently uses 4, 7, 12 and 21.

Frequency Reuse

- Geometry of the hexagonal cells is such that to cover adjacent areas completely, N can have only some of the values.
- N should satisfy the relationship,

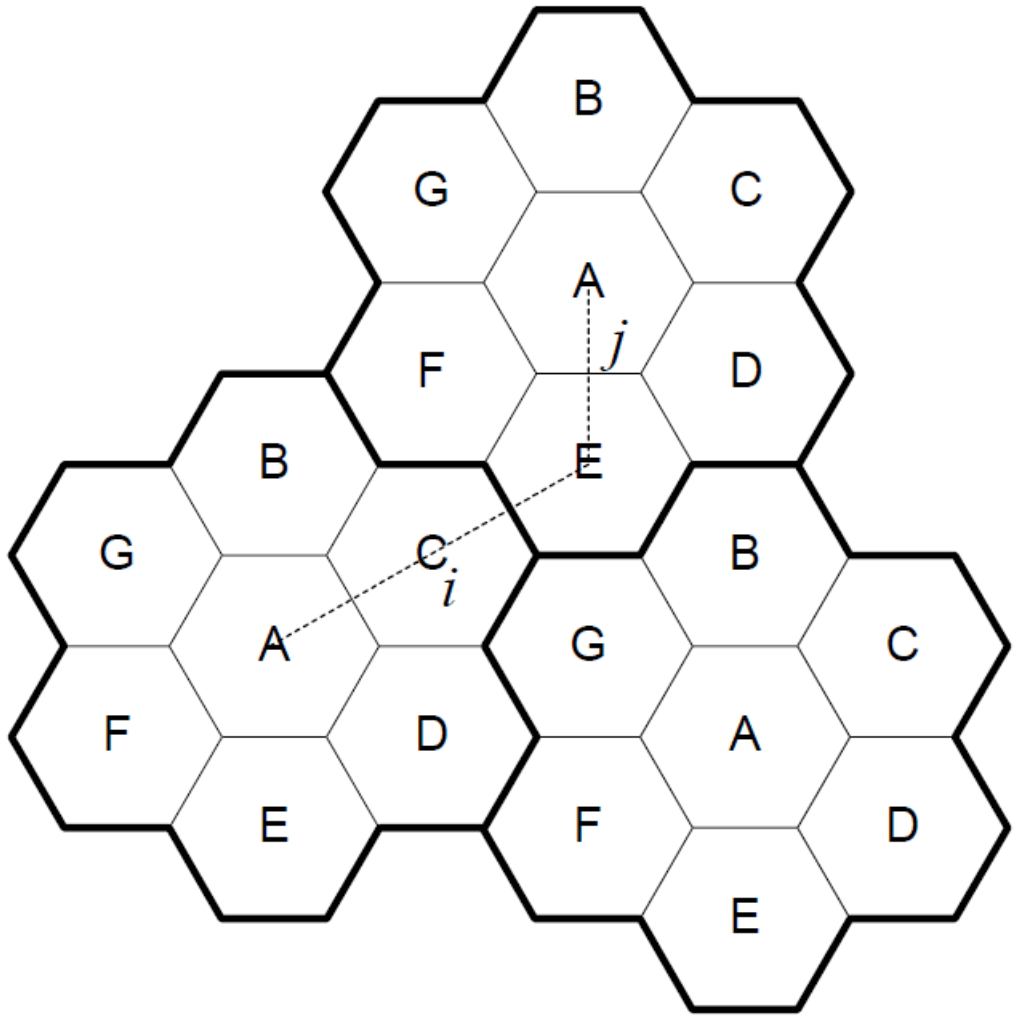
$$N = i^2 + i\,j + j^2$$

where i and j are positive integers. Typical values of N are 4,7,12 etc.

- To draw the cell pattern given *i* and *j* and to find nearest co-channel neighbour

1. Move *i* cells across hexagons.
2. Turn 60º CCW and move *j* cells.

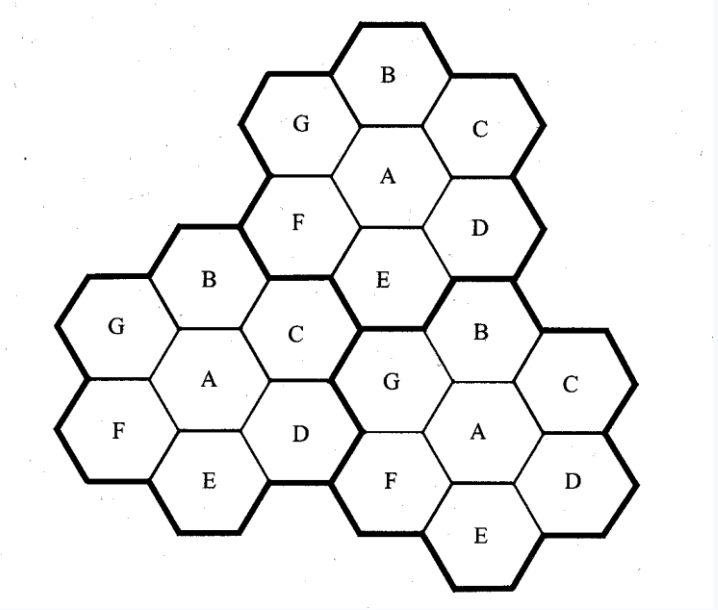
Frequency Reuse (N=7, i=2, j=1)



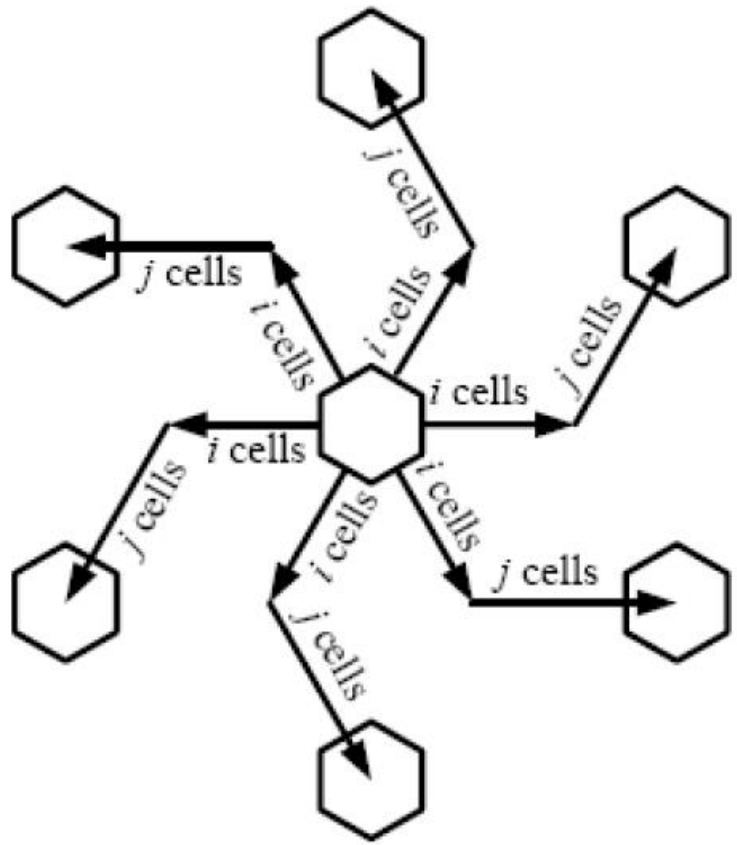
Frequency Reuse

- Each cellular base station is allocated a group of radio channels within a small geographic area called a *cell*.
- Neighboring cells are assigned different channel groups.
- By limiting the coverage area to within the boundary of the cell, the channel groups may be reused to cover different cells.
- Keep interference levels within tolerable limits.
- Frequency reuse or frequency planning

  - •seven groups of channel from A to G
  - •footprint of a cell - actual radio coverage
  - •omni-directional antenna v.s. directional antenna

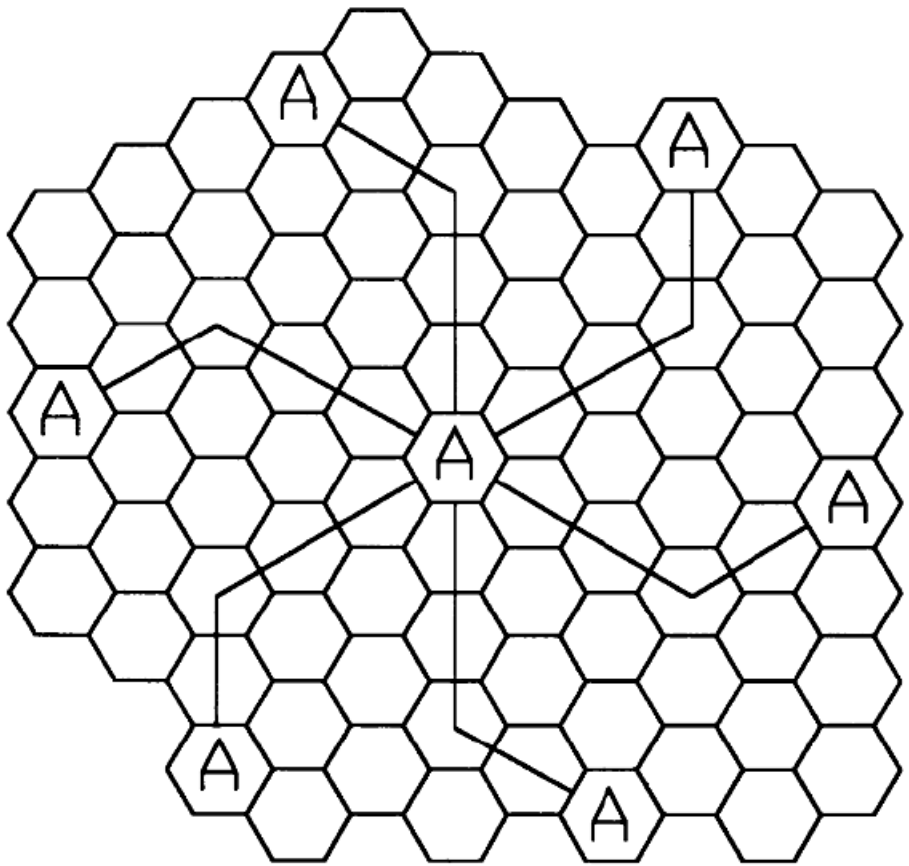


Frequency Reuse



Nearest co-channel

Example N=19
(i=3, j=2)



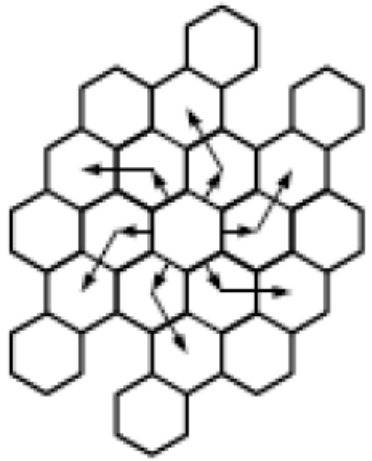
To find the nearest co-channel neighbors of a particular cell:

- move i cells along any chain or hexagon.
- then turn 60 degrees counterclockwise and move j cells.

Nearest co-channel

$i = 1, j = 1$

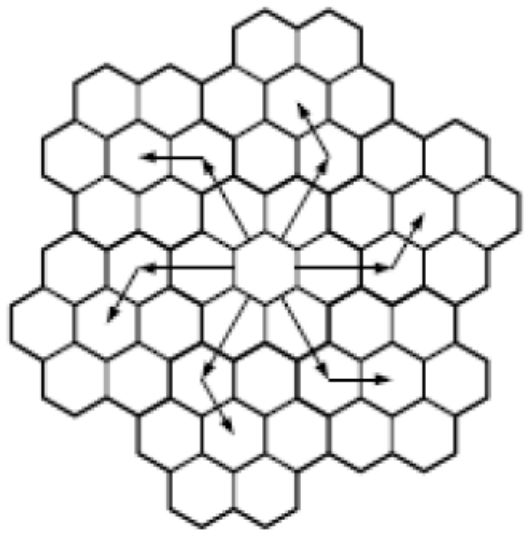
$N = 3$



$i = 2, j = 0$

$N = 4$





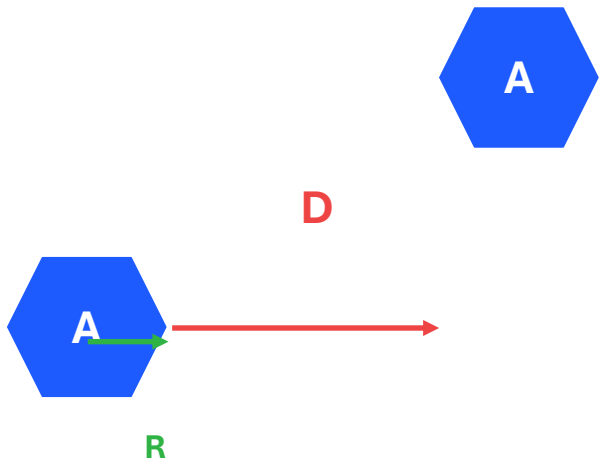
$i = 2, j = 1$

$N = 7$

Reuse distance

GEOMETRY

Co-channel cells must be separated by a minimum distance



$$D / R = \sqrt{(3N)}$$

- D = reuse distance between co-channel cells
- R = cell radius
- N = cluster size
- Larger N ⇒ larger D/R ⇒ lower interference

This is the central engineering trade-off: choose N to balance capacity and signal quality.

Capacity model

CAPACITY

Translate spectrum and cluster size into channels per cell and system capacity

T

total duplex channels

Spectrum budget converted into usable full-duplex channel pairs.

channels / cell = T / N

N

cluster size

More cells per cluster means fewer channels per cell but lower interference.

reuse factor = 1/N

M

cluster replications

If the cluster is replicated M times, total network capacity grows.

system capacity = M × T

Worked example: given data

EXAMPLE

FDD system with 33 MHz total bandwidth and 25 kHz simplex channels

Total allocated spectrum

33 MHz = 33,000 kHz

Simplex channel bandwidth

25 kHz

Full-duplex voice/control channel

2 simplex channels: uplink + downlink

Cluster sizes to test

N = 4, 7, 12

Number of base stations

50

Coverage area

250 km^2

Always convert units first and remember that FDD full duplex needs a pair of simplex channels.

Step 1 — total duplex channels

CALCULATION

Convert spectrum into full-duplex channel pairs

simplex channels = 33,000 kHz / 25 kHz = 1320

full-duplex channels = 1320 / 2 = 660

- Why divide by 2? FDD uses separate uplink and downlink simplex channels to create one two-way voice/control channel.
- Therefore, the system has T = 660 full-duplex channels available before cluster allocation.

Step 2 — channels per cell

RESULTS

Divide total duplex channels by the cluster size N

N = 4

660 / 4

165

channels per cell

highest capacity, more interference

N = 7

660 / 7

≈ 94

channels per cell

balanced classic plan

N = 12

660 / 12

55

channels per cell

lower interference, lower capacity

Step 3 — total channel capacity with 50 base stations

CAPACITY

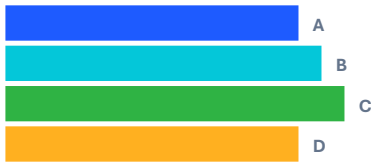
Approximate full-duplex channel capacity over the installed cells

Cluster size	Channels/cell	50 BS capacity
N = 4	165	8,250
N = 7	94	4,700
N = 12	55	2,750

These values assume every base station corresponds to one cell and has the calculated number of channels.

Trade-off visible in the numbers

- N = 4 gives almost 3× the capacity of N = 12.
- But smaller N places co-channel cells closer together.
- Final design depends on traffic demand, quality target, cell radius and terrain.



Step 4 — reuse distance from

c 4) **Reuse distance** D for each N

(a) Area per cell and cell radius R

$$A_{\text{cell}} = \frac{250}{50} = 5 \text{ km}^2$$

$$A_{\text{hex}} = \frac{3\sqrt{3}}{2} R^2 \Rightarrow R = \sqrt{\frac{2A}{3\sqrt{3}}} = \sqrt{\frac{2 \times 5}{3\sqrt{3}}} \approx \boxed{1.387 \text{ km}}$$

(b) Reuse distance D

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

- $N = 4$: $D = 1.387 \times \sqrt{12} \approx 1.387 \times 3.464 \approx \boxed{4.806 \text{ km}}$
- $N = 7$: $D = 1.387 \times \sqrt{21} \approx 1.387 \times 4.583 \approx \boxed{6.357 \text{ km}}$
- $N = 12$: $D = 1.387 \times \sqrt{36} = 1.387 \times 6 \approx \boxed{8.324 \text{ km}}$

Frequency planning workflow

WORKFLOW

A practical sequence for designing a reuse plan



Estimate demand

traffic per area + busy hour

Choose cell size

coverage, terrain and tower placement

Select N

capacity vs interference

Assign groups

avoid adjacent reuse

Validate

field measurements and optimization

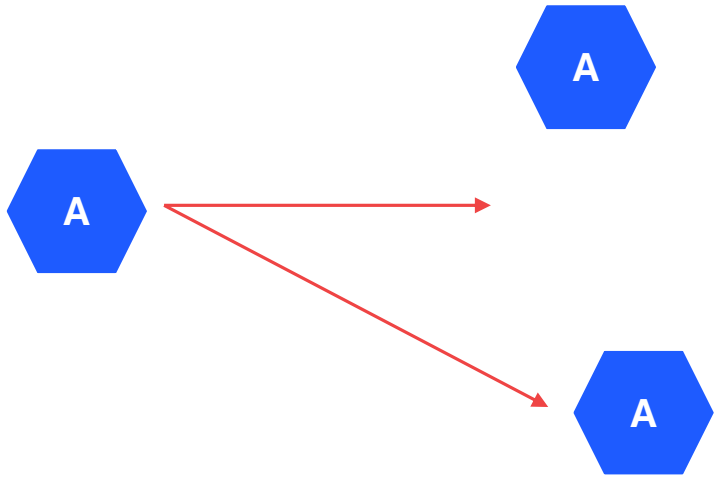
Frequency reuse is designed, deployed and then continuously tuned as traffic grows and field conditions change.

Interference in cellular systems

INTERFERENCE

Reuse increases capacity, but interference limits quality

Co-channel interference



same frequencies reused

Adjacent-channel interference



- Occurs when nearby frequencies leak into each other due to imperfect filtering or poor allocation.
- Reduced by guard bands, filtering and careful channel planning.

Reducing co-channel interference

MITIGATION

Co-channel cells must be separated or made less visible to each other

Increase N

larger reuse distance D

Sectorization

directional antenna beams reduce interferers

Power control

lower transmit power limits spillover

Antenna planning

height, tilt and location optimization

Signal quality target ⇄ Spectrum efficiency target

Channel assignment strategies

ASSIGNMENT

How channels are allocated to cells and users

Fixed channel assignment

- Each cell has a predetermined set of channels.
- New calls use only the unused channels assigned to that cell.
- If all assigned channels are busy, the call is blocked.
- Simple but less flexible under uneven traffic.

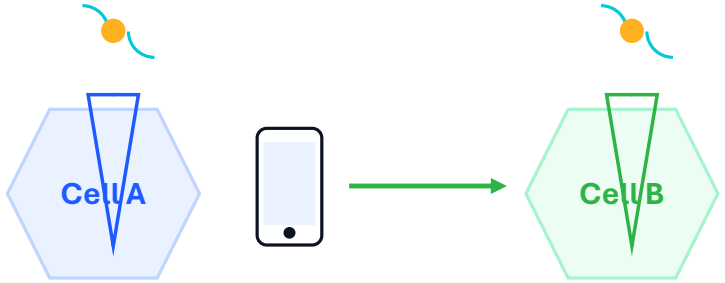
Dynamic channel assignment

- Channels are not permanently tied to cells.
- The network assigns channels based on request and current conditions.
- Can reduce blocking and increase capacity.
- Requires more coordination and computation.

Handoff / handover

MOBILITY

Keep a call alive as the mobile moves across cell boundaries



The network transfers the call from one radio channel or base station to another without alerting the user.

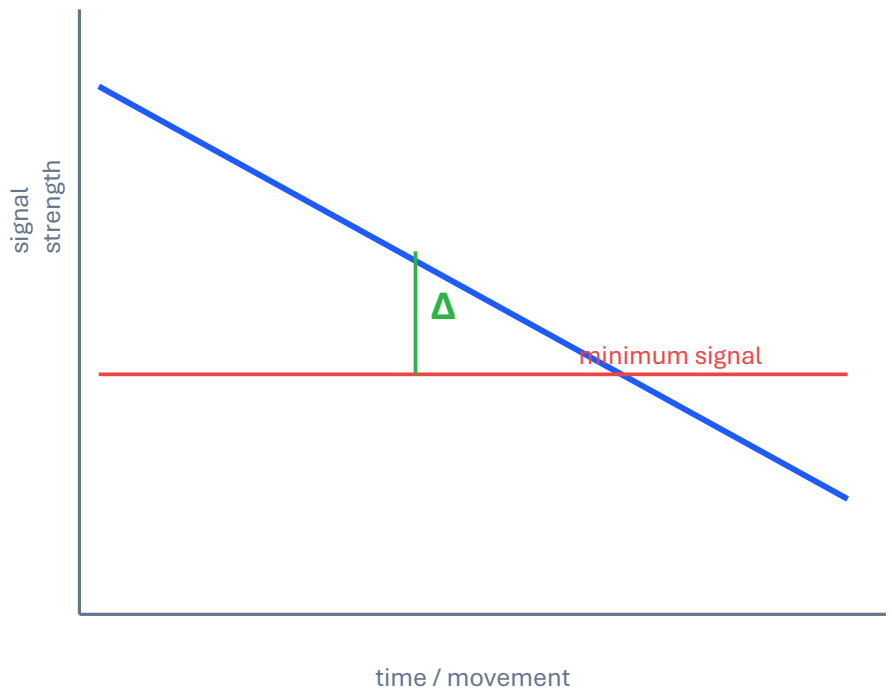
Why handoff matters

- Avoid call drops
- Maintain service continuity
- Balance traffic across cells
- Support fast-moving users

Handoff threshold Δ

THRESHOLD

Choose the right moment to start handoff



Δ too small

- Handoff starts too late
- Insufficient time to complete
- Higher call drop probability

Δ too large

- Handoff starts too early
- More unnecessary handoffs
- Greater MSC / network load

Hard vs soft handover

TYPES

Two common mobility mechanisms

Hard handover

- Break-before-make behavior.
- Mobile switches to a new sector/cell on a different frequency.
- Used in many inter-frequency mobility cases.
- Brief interruption must be tightly controlled.

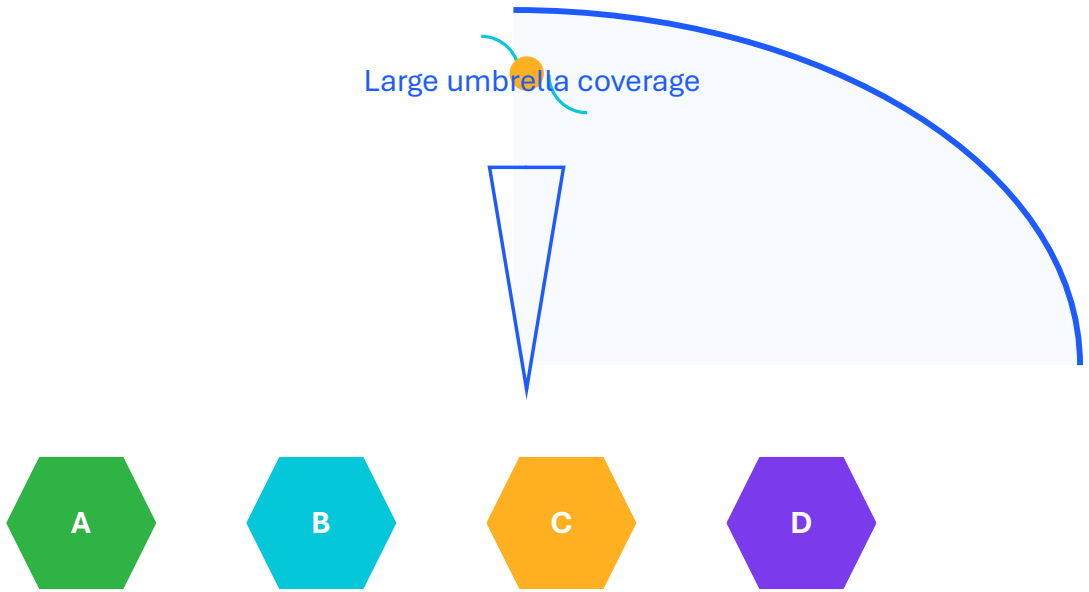
Soft handover

- Make-before-break behavior.
- Mobile can communicate with more than one sector/cell on the same frequency.
- Can improve reliability near cell edges.
- Requires extra radio/network resources.

Umbrella cells

MOBILITY LAYER

Layer large and small cells to support mixed mobility

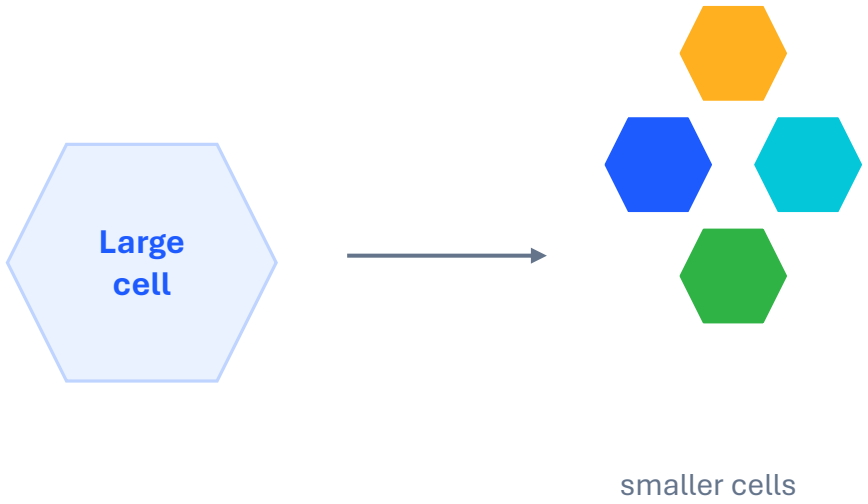


- Fast-moving users can stay on the large umbrella cell to reduce frequent handoffs.
- Slow/stationary users can be served by smaller cells to increase capacity.
- Useful in highways, dense urban areas and hotspots.

Capacity expansion: cell splitting

EXPANSION

Increase capacity by reducing cell size and adding more base stations



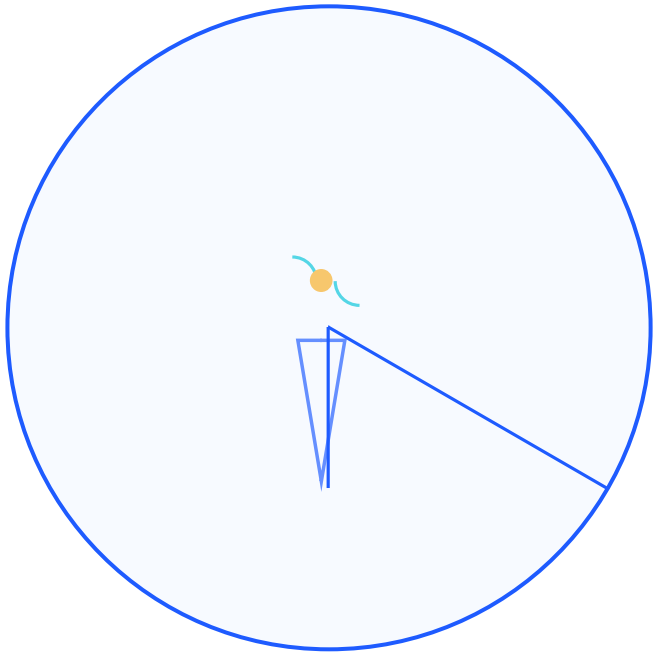
- More base stations in the same area.
- Antenna height and transmit power are reduced.
- Traffic capacity increases because the same frequency plan is reused over a smaller geography.
- Works well as demand grows gradually.

Cell splitting is a geometry re-scaling technique: more cells per km^2 means more capacity per km^2.

Capacity expansion: sectorization

EXPANSION

Keep the same cell radius but use directional antennas



3 × 120° sectors

- Omni-directional antenna is replaced by multiple directional antennas.
- Each beam radiates within a selected sector (often 120° or 60°).
- Directional beams reduce the number of dominant co-channel interferers.
- Cell radius R can remain unchanged.

Choosing an expansion technique

COMPARISON

Different techniques solve different capacity and interference problems

Technique	Main action	Best when	Trade-off
Reuse planning	Choose N and channel groups	Initial network design	Capacity vs interference
Cell splitting	Smaller cells + more BS	Traffic grows in hotspots	More sites and cost
Sectorization	Directional antenna beams	Interference limits quality	Antenna complexity
Umbrella cells	Layer large + small cells	Fast and slow users mix	More mobility control

A good network usually combines all of these techniques over time rather than relying on one method.

Key takeaways

- Cells and clusters enable planned spectrum reuse.
- Reuse factor is 1/N; common N values come from hexagonal geometry.
- Reuse distance follows $D/R = \sqrt{(3N)}$.
- Capacity rises when N decreases, but interference usually rises too.
- Handoff and expansion techniques keep the network usable as users move and traffic grows.

Quick review questions

- Why can’t adjacent cells share the same frequency group?
- For N = 7, what is D/R?
- Why does FDD divide simplex channels by 2?
- When would you prefer sectorization over cell splitting?