Chapter 4: Cellular System Design Fundamentals

Frequency Reuse or Frequency Planning

What is Frequency Reuse?

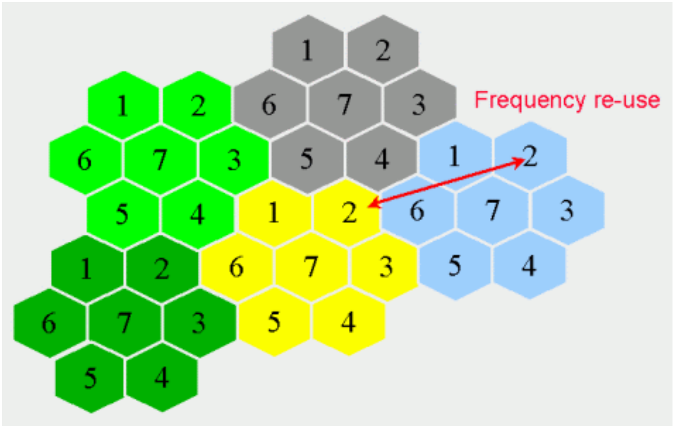
Frequency Reuse is the practice of using the same frequency channels in different cells, spaced sufficiently apart, to maximize spectrum efficiency.

- Limited spectrum is reused across non-adjacent cells
- Enables large geographic coverage and more users

Visualizing Reuse – Cellular Layout

- Cells arranged in a hexagonal pattern
- Each cell has a set of frequencies

Reuse Pattern	Cluster Size
1 2 3 4 5 6 7	N=7



Cluster Size *N*

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

Where:

- i, j = non-negative integers
- N = number of unique frequency cells in one cluster

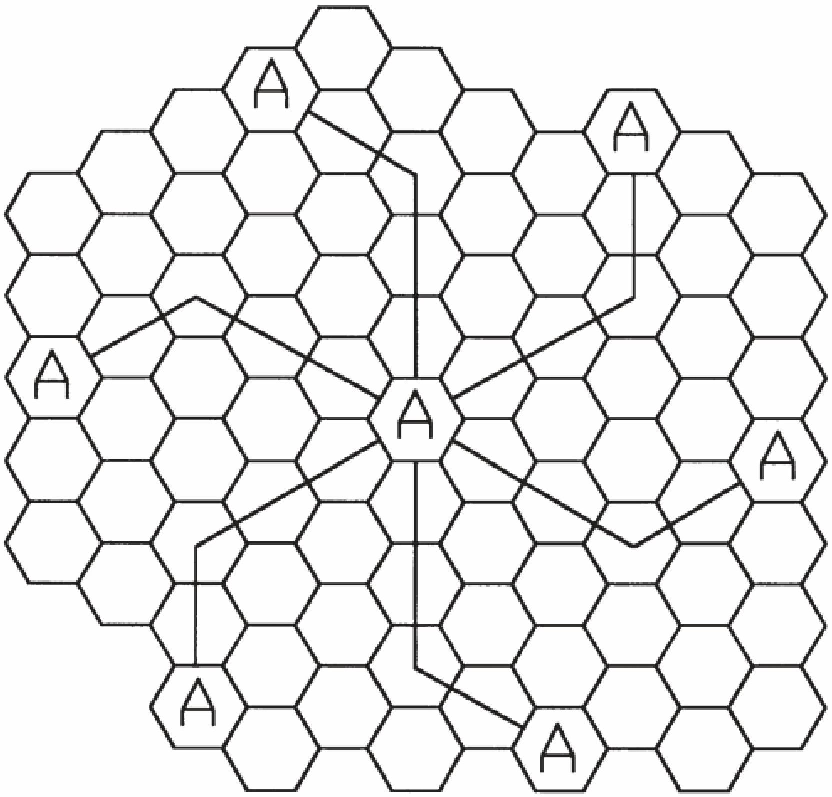
Examples

- $i = 2, j = 1 \Rightarrow N = 7$
- $i = 1, j = 2 \Rightarrow N = 7$

- Common values 3, 4, 7, 12

Method of locating co-channel cells in a cellular system

- For i = 3 and j =2 (i.e., N = 19)
- To find the nearest co-channel neighbors of a particular cell, one must do the following:
  - (1) move i cells along any chain of hexagons and then
  - (2) turn 60 degrees counter-clockwise and move j cells.



Example question

Q) If a total of 33 MHz of bandwidth is allocated to a particular FDD cellular telephone system which uses two 25 kHz simplex channels to provide full duplex voice and control channels, compute the number of channels avail able per cell if a system uses (a) four-cell reuse, (b) seven-cell reuse, and (c) 12-cell reuse. If 1 MHz of the allocated spectrum is dedicated to control channels, determine an equitable distribution of control channels and voice channels in each cell for each of the three systems.

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Given: Total bandwidth = 33 MHz

Channel bandwidth = 25 kHz x 2 simplex channels = 50 kHz/duplex channel

Total available channels = 33,000/50 = 660 channels

(a) For N=4,

total number of channels available per cell = 660/4 = 165 channels.

(b) For N=7,

total number of channels available per cell = 660/7 = 95 channels.

(c) For N = 12,

total number of channels available per cell = 660/12 = 55 channels.

Frequency Reuse Factor

$$Reuse\ Factor = \frac{1}{N}$$

- For N = 7, reuse factor = 1/7
- Smaller N → more frequent reuse → higher capacity
- Larger N → less interference → better QoS

Trade-off between capacity and interference

Reuse Distance and Interference

Reuse Distance D

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

Where:

- D: Distance between co-channel cells
- R: Cell radius
- N: Cluster size

Co-channel cells must be **far enough apart** to reduce interference

Example Calculation – Reuse Distance

Problem:

If cell radius R=1.5 km, and N=7,

Find the reuse distance D

$$\mathrm{D} = 1.5 * \sqrt{(3 * 7)}$$
$$= 6.87 \text{ km}$$

Co-channel Interference

- Occurs when same frequencies are reused too close
- Interference depends on:
  - Distance between co-channel cells (reuse distance D)
  - Number of interfering cells
  - Antenna height/pattern

Trade-Off: Capacity vs Interference

Increase N	Decrease N
Less interference	More interference
Lower capacity	Higher capacity
Higher QoS	Lower QoS

Practical Implications

Real-World Application of Frequency Reuse

Used in:

- GSM, LTE, 5G NR
- Urban networks (small cells = lower N)
- Rural networks (large N, larger D)

Dynamic Frequency Reuse and Adaptive Antennas in modern networks

Channel Assignment Strategies

Introduction to Channel Assignment

What is Channel Assignment?

- Channel assignment refers to the method by which frequency channels are allocated to cells and users in a cellular system.
- It determines:
  - Which frequencies are used in which cells
  - How calls are allocated frequency channels
  - How to minimize interference and maximize reuse

Introduction to Channel Assignment

Key Goals of Assignment

- Efficient spectrum utilization
- Minimize co-channel interference
- Adapt to traffic demands
- Ensure seamless handoffs
- Maintain QoS and reduce blocking

Types of Channel Assignment Strategies

Fixed Channel Assignment (FCA)

In FCA:

- Each cell is preassigned a group of frequencies
- Channels are static and reused based on cluster patterns (e.g., N = 7)

Simple to implement but not flexible.

Fixed Channel Assignment (FCA)

Advantages:

- Simple
- Predictable interference

Disadvantages:

- Poor utilization under uneven traffic
- High blocking in busy cells

Fixed Channel Assignment (FCA)

Suppose 140 total channels, 7-cell reuse pattern → Each cell gets 140/7=20 fixed channels

- If Cell A gets 25 users simultaneously → 5 get blocked
- Meanwhile, Cell B may have only 8 users → 12 channels unused

No dynamic sharing → **inefficient utilization**

Dynamic Channel Assignment (DCA)

In DCA:

- No fixed channels are assigned to cells
- Channels are assigned from a central pool dynamically based on need and availability

Dynamic Channel Assignment (DCA)

Advantages:

- Better traffic adaptation
- Fewer blocked calls
- Efficient spectrum use

Disadvantages:

- Complex real-time channel allocation
- Needs centralized control and real-time monitoring

Dynamic Channel Assignment (DCA)

DCA Operation

- When a call request comes in:
  - Base Station sends a request to MSC
  - MSC checks which channel is available and has minimum interference
  - Channel is temporarily assigned to the cell
  - Released back to pool after call ends

DCA adjusts to load, but needs powerful algorithms

Hybrid Channel Assignment (HCA)

Combination of FCA and DCA

- Each cell gets a few fixed channels
- Additional channels assigned dynamically as needed

Offers a balance between simplicity and efficiency

Comparison Table

Strategy	Flexibility	Complexity	Interference Control	Spectrum Efficiency
FCA	Low	Low	Moderate	Low
DCA	High	High	High	High
HCA	Medium	Medium	High	High

Real-World Relevance

Channel Assignment in Modern Systems

Examples:

- **GSM**: Uses Hybrid strategy with frequency hopping
- **CDMA/3G**: Does not assign channels in the same sense; users share spectrum via codes
- **4G/5G (OFDMA)**: Resource blocks dynamically assigned

Modern networks use real-time algorithms for optimal resource use

Example Problem – FCA Blocking

Problem:

A system has 100 channels with reuse factor N = 5.

Each cell gets 20 channels.

In Cell X, 25 users try to make calls at the same time.

Q) How many calls get blocked?

Handoff Strategies in Cellular Systems

Understanding Handoff

What is a Handoff?

- A handoff (handover) occurs when an active call or data session is transferred from one base station (BS) to another as the user moves through the network.
- Goal: Maintain continuous connectivity without dropping the call

When is Handoff Needed?

Handoff is triggered when:

- Signal strength of the current BS drops below threshold
- Neighboring cell's signal is stronger
- User is moving out of current cell's coverage
- Load balancing or interference conditions require change

Handoff helps optimize call quality and resource usage

Types of Handoff

Type	Description	Used In
Hard Handoff	Break before make (disconnect → reconnect)	GSM, TDMA
Soft Handoff	Make before break (connected to both BSs)	CDMA, 3G
Softer Handoff	Between sectors of the same BS	CDMA

Handoff Decision Criteria

Handoff Decision Metrics

Parameters used in deciding handoff:

- Received Signal Strength (RSS)
- Signal-to-Interference Ratio (SIR)
- Bit Error Rate (BER)
- Velocity of user
- Thresholds and hysteresis values

Must avoid ping-pong effect (frequent handoffs)

Handoff Timing – Call Drop vs. Poor Quality

If handoff is too **late**:

- Call may drop due to low signal

If handoff is too **early**:

- Increases network load, may lead to instability

Need to balance: **timeliness vs. stability**

Example:
RSS drops below –85 dBm → initiate handoff decision

Prioritization in Handoff

In a congested network:

- New call requests may be blocked
- Handoff calls are prioritized to prevent drops
- Guard channels may be reserved for handoff only

Ensures ongoing calls are less likely to drop

Types of Handoff Strategies

Network-Controlled Handoff (NCHO)

Handoff decisions are made by the MSC/network, based on measurements from BSs.

- Accurate, centralized
- Higher processing load and latency

Used in: **1G analog systems (e.g., AMPS)**

Mobile-Assisted Handoff (MAHO)

Mobile Station measures RSS from surrounding BSs and assists the network in decision-making.

Used in: GSM and most 2G/3G systems

- Quicker decisions
- Efficient for fast-moving users

Mobile-Controlled Handoff (MCHO)

Mobile Station decides and initiates the handoff based on signal measurements.

Used in: DECT and some microcellular systems

- Fast and local
- Less coordinated, risk of ping-pong

Handoff in Modern Networks

In CDMA and 3G systems, soft handoff allows:

- Multiple BSs to simultaneously serve the user
- Handoff happens seamlessly
- Combines signals to improve quality

In 4G/5G, handoff is tightly integrated with IP mobility and resource scheduling

Example Scenario

A user is on a call, moving from Cell A to Cell B.

- At –83 dBm RSS from A and –80 dBm from B
- System checks SIR and BER
- If conditions are met, handoff initiated

If successful: call continues uninterrupted
If failed: call is dropped

Mid Term

Interference and System Capacity

Introduction

- Interference is the major limiting factor in the performance of cellular systems.
- Sources of interference include
  - another mobile in the same cell,
  - a call in progress in a neighboring cell,
  - other base stations operating in the same frequency band, or
  - any noncellular system which inadvertently leaks energy into the cellular frequency band.
- Affects call quality, data rates, and overall capacity.

Introduction

- Interference on voice channels causes **cross talk**, where the subscriber hears interference in the background due to an undesired transmission.
- On control channels, interference leads to missed and blocked calls due to errors in the digital signaling.

Types of interference

- Co-channel interference (from nearby cells using the same frequency)
- Adjacent-channel interference (from nearby frequencies)

Types of Interference in Cellular Systems

Type	Source	Solution
Co-Channel Interference	Reuse of same frequency in nearby cells	Increase reuse distance (D), reduce reuse factor (N)
Adjacent-Channel Interference	Imperfect filtering of nearby frequency channels	Guard bands, better filters
Other-cell Interference	Signals from neighboring cells	Handoff and power control

Co-channel Interference

- Occurs due to frequency reuse.
- Cannot be eliminated, but minimized by:
  - Increasing the reuse distance (D)
  - Using directional antennas
- Signal-to-Interference Ratio (SIR) is the key metric.

Co-channel Reuse Ratio

- When the size of each cell is approximately the same and the base stations transmit the same power, the co-channel interference ratio is independent of the transmitted power and becomes a function of the radius of the cell (R) and the distance between centers of the nearest co-channel cells (D).
- By increasing the ratio of D/R, the spatial separation between co-channel cells relative to the coverage distance of a cell is increased.
- Thus, interference is reduced from improved isolation of RF energy from the co-channel cell.
- The parameter Q, called the co-channel reuse ratio, is related to the cluster size . For a hexagonal geometry

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

Co-channel Reuse Ratio for Some Values of N

	Cluster Size (N)	Co-channel Reuse Ratio (Q)
$i = 1,\ j = 1$	3	3
$i = 1,\ j = 2$	7	4.58
$i = 0,\ j = 3$	9	5.20
$i = 2,\ j = 2$	12	6

SIR Formula in Co-Channel Interference

$$SIR = \frac{(^{D}/_{R})^{n}}{i}$$

Where:

- R = radius of cell
- D = distance between co-channel cells
- n = path loss exponent (typically 3 to 4)
- i = number of interfering co-channel cells

Alternately:

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

Example Problem

Given:

- Cluster size N=7
- Path loss exponent n=4
- Calculate SIR assuming 6 first-tier interferers at equal distance

Solution:

?

Example Problem

Given:

- Cluster size N=7
- Path loss exponent n=4
- Calculate SIR assuming 6 first-tier interferers at equal distance

Solution:

$$Q = \frac{D}{R} = \sqrt{3N} = \sqrt{21} \approx 4.58$$

$$SIR = \frac{\left({}^{D}/_{R}\right)^n}{i} = \frac{(4.58)^4}{6} = \frac{441.9}{6} = 73.65 \approx 18.67\ dB$$

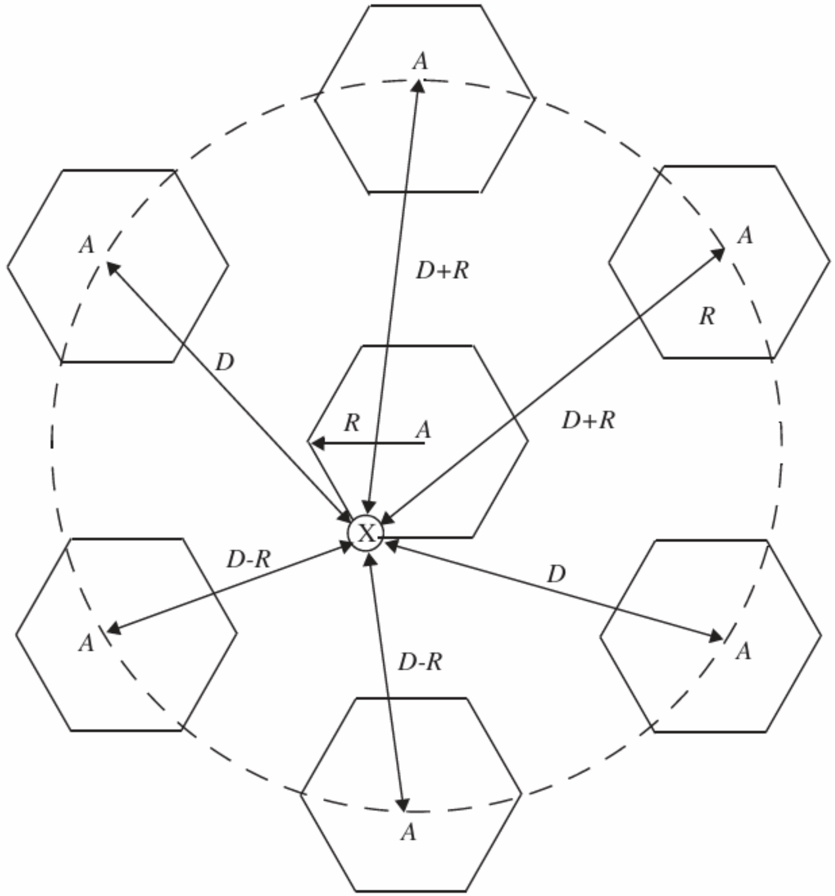

Illustration of the first tier of co-channel cells for a cluster size of N = 7. An approximation of the exact geometry is shown here, whereas the exact geometry is given. When the mobile is at the cell boundary (point X), it experiences worst case co-channel interference on the forward channel. The marked distances between the mobile and different co-channel cells are based on approximations made for easy analysis.

Example Problem

Q) If a signal-to-interference ratio of 15 dB is required for satisfactory forward channel performance of a cellular system, what is the frequency reuse factor and cluster size that should be used for maximum capacity if the path loss exponent is (a) $n = 4$, (b) $n = 3$? Assume that there are six co channel cells in the first tier, and all of them are at the same distance from the mobile. Use suitable approximations.

Example Problem

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A) n= 4

First, let us consider a seven-cell reuse pattern.

Using Equation, the co-channel reuse ratio DIR = 4.583.

Using Equation, the signal-to-noise interference ratio is given by

$$S/I = (1/6) \times (4.583)^4 = 75.3 = 18.66 \text{ dB}$$

Since this is greater than the minimum required S/I, N = 7 can be used.

Example Problem

Q) If a signal-to-interference ratio of 15 dB is required for satisfactory forward channel performance of a cellular system, what is the frequency reuse factor and cluster size that should be used for maximum capacity if the path loss exponent is (a) n = 4, (b) n = 3? Assume that there are six co channel cells in the first tier, and all of them are at the same distance from the mobile. Use suitable approximations.

B) n= 3

First, let us consider a seven-cell reuse pattern.

Using Equation, the signal-to-interference ratio is given by

$$S/I = (1/6) \times (4.583)^3 = 16.04 = 12.05 \text{ dB}$$

Since this is less than the minimum required S/I, we need to use a larger N.

Using Equation, the next possible value of N is 12, (i = j = 2).

The corresponding co-channel ratio is given by Equation as

$$D/R = 6.0$$

Using Equation, the signal-to-interference ratio is given by

$$S/I = (1/6) \times (6)^3 = 36 = 15.56 \text{ dB}$$

Since this is greater than the minimum required S/I, N= 12 is used.

Channel Planning for Wireless Systems

Channel planning is the process of allocating frequencies to cells in a way that:

- Minimizes co-channel interference
- Maximizes spectral efficiency
- Maintains Quality of Service (QoS)

Importance of Channel Planning

Essential for optimizing coverage, capacity, and QoS

- Affects:
  - Frequency reuse pattern
  - Cell layout and cluster size
  - Interference levels

Key Terminology

Term	Description
Cluster Size (N)	Number of cells in a group using different frequencies
Reuse Distance (D)	Minimum distance between co-channel cells
Co-channel Interference	Interference from cells using same frequencies

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

- Where:
- D: Reuse distance
- R: Cell radius
- N: Cluster size

Cluster Size and Frequency Allocation

- Smaller N = higher capacity, but more interference
- Larger N = less interference, but lower capacity
- Trade-off: Capacity vs Interference
- **Example:**
  If total available channels = 300
  If cluster size N=7, then each cell gets $300/7 \approx 43$ channels

Practical Guidelines in Channel Planning

- Avoid assigning same channel to adjacent cells
- Implement sectoring or directional antennas to reduce interference
- Include guard bands where necessary
- Consider terrain, population density, and traffic load

Channel Planning Tools

- Computer-aided planning (CAP) software
- Input: terrain data, interference models, antenna parameters
- Output: cell coverage maps, frequency assignments

f1/f2 Frequency Assignment

What is f1/f2?

- In CDMA systems, two frequency carriers — f1 and f2 — are alternately assigned to adjacent cells.
- This strategy helps manage interference and increase capacity.

How it works:

- Cell A uses f1
- Cell B uses f2
- Cell C uses f1 again
  → This alternating assignment reduces inter-cell interference.

Purpose of f1/f2 Scheme

- Helps with soft handoff and load balancing
- Reduces cross-cell interference in dense urban environments
- Ensures frequency diversity in adjacent cells

Cell Breathing (CDMA)

Definition:

- In CDMA systems, the cell coverage area dynamically changes (breathes) based on traffic load.

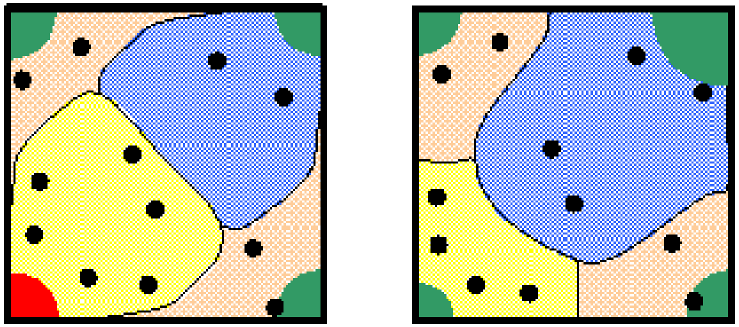
Why it happens:

- CDMA uses power control — as more users connect, total power increases
- Higher power = more interference = smaller effective coverage
- Lower traffic = lower interference = larger cell coverage

Cell Breathing (CDMA)

Visualizing Cell Breathing

- Two states of a CDMA cell:
  - Low load → large radius
  - High load → small radius
- Looks like the cell is "breathing"



Implications of Cell Breathing

- Network must handle dynamic coverage changes

Requires:

- Adaptive handoff strategies
- Smart capacity planning
- Real-time load monitoring

Handled by:

- Power control algorithms
- Admission control (limiting users in high traffic)

Adjacent Channel Interference (ACI)

- Results from imperfect filters allowing adjacent channels to bleed into each other.

Minimized by:

- Guard bands
- Careful frequency planning
- Tight receiver filtering

Adjacent Channel Interference (ACI)

What is Bleed-over?

- A form of interference caused by signals from a channel spilling into adjacent channels.

- Why it happens:
  - Imperfect filtering in transmitter/receiver
  - Overlapping bandwidths or receiver nonlinearity

- Also called: Adjacent Channel Interference (ACI) or Bleed-over

Strategies to Reduce Interference

- Increase cluster size (reduce frequency reuse)
- Use sectoring (dividing cells into 3 or 6 sectors)
- Employ power control and handoff algorithms
- Utilize interference cancellation techniques

Trade-off Between Interference and Capacity

Larger Cluster Size (N↑)	Smaller Cluster Size (N↓)
Less interference	More interference
Lower capacity	Higher capacity
Higher SIR	Lower SIR

- Optimal cluster size balances capacity and SIR.

System Capacity

Defined as maximum number of simultaneous users.

Dependent on:

- Bandwidth
- Channel bandwidth
- Reuse factor N
- Cell splitting and sectoring

Example: Calculating Capacity

Given:

- Total Bandwidth: 25 MHz
- Channel Bandwidth: 25 kHz
- Cluster Size: N=7
- Number of cells = 49

Example: Calculating Capacity

Given:

- Total Bandwidth: 25 MHz
- Channel Bandwidth: 25 kHz
- Cluster Size: N=7
- Number of cells = 49

- **Solution:**

  Total Channels=$25\times10^6/25\times10^3$=1000

  Channels per cell=1000/7≈143

  Total capacity=143×49≈7,007users

Near-Far Effect

What is Near-Far Effect?

- In CDMA, multiple users transmit on the same frequency using different codes.

Problem: A user close to the base station (near) may drown out a far user's signal at the receiver due to higher signal strength.

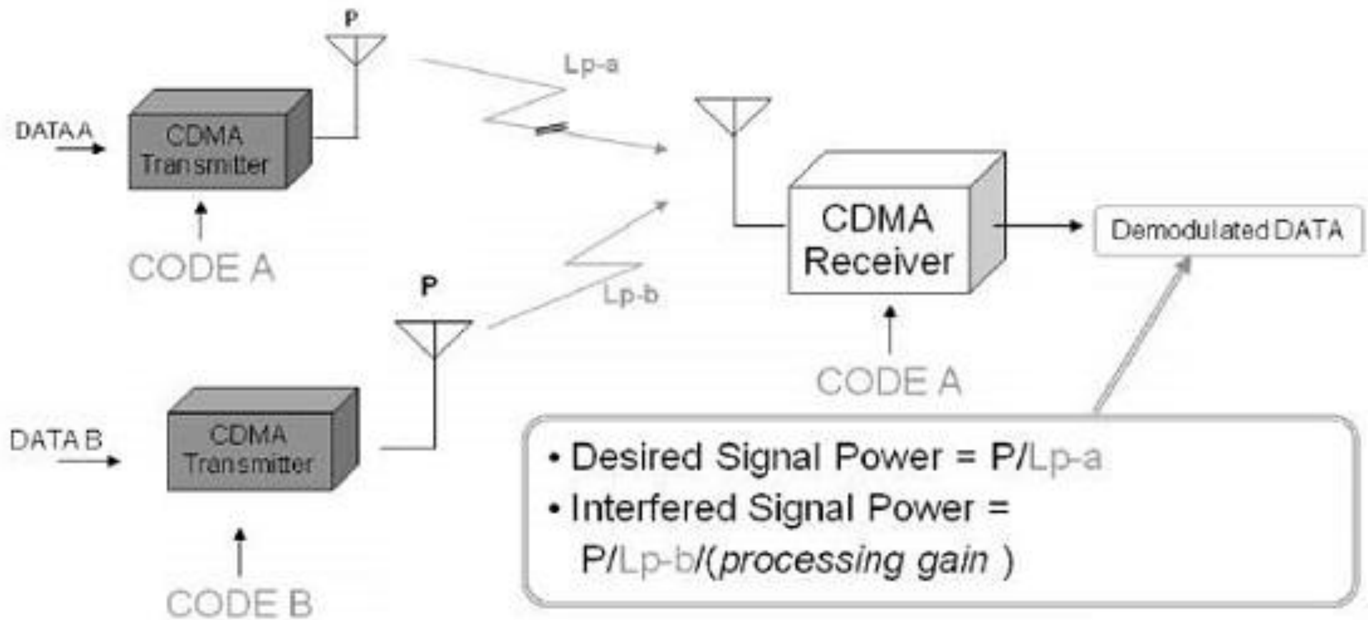
Cause:

- Signals from near users arrive much stronger than those from distant users.
- Receiver struggles to decode weak signals.

Solution:

- Power Control is mandatory in CDMA to equalize received power from all users.

Near-Far Effect



When user B is close to the receiver and user A is far from the receiver, Lp-a could be much bigger than Lp-b. In this case, desired signal power is smaller than the interfered power.

Power Control for Reducing Interference

- In practical cellular radio and personal communication systems, the power levels transmitted by every subscriber unit are under constant control by the serving base stations.
- This is done to ensure that each mobile transmits the smallest power necessary to maintain a good quality link on the reverse channel.
- Power control not only helps prolong battery life for the subscriber unit, but also dramatically reduces the reverse channel S/I in the system.
- Power control is especially important for emerging CDMA spread spectrum systems that allow every user in every cell to share the same radio channel.

ACI vs Co-Channel Interference

Feature	Co-Channel Interference	Adjacent Channel Interference
Same Frequency?	Yes	No (close, but different)
Managed by	Frequency Reuse (N)	Filter Design + Channel Plan
Common in	All cellular systems	Narrowband systems
Solution	Reuse distance D	Guard bands, filtering

Trunking and Grade of Service

Introduction to Trunking

What is Trunking?

- A technique that allows a common pool of channels to be shared by multiple users.
- Originates from telephone networks.

Why Trunking?

- Economizes on channel usage.
- Maximizes resource efficiency.

Trunking vs Dedicated Channels

Feature	Dedicated Channels	Trunking System
Channel per user	Fixed	Shared
Efficiency	Low	High
Blocking Probability	Low (but wasteful)	Controlled (optimized)

Real-Life Analogy

Analogy: Bank Counters

- Dedicated: One counter per customer — inefficient.
- Trunked: Multiple customers share available counters — waiting time may occur, but more efficient.

Grade of Service (GoS)

What is GoS?

- A measure of how well the network meets service demand.
- Defined as the probability of call blocking when all channels are busy.

Typical GoS Values:

- 0.02 → 2% calls blocked
- 0.01 → 1% calls blocked (better GoS)

Blocking Probability

Why is blocking important?

- Represents the user experience and network design quality.

Tradeoff:

- Low blocking → Requires more channels → Costly
- High blocking → Fewer channels → Poor QoS

Erlang Traffic Theory Basics

Erlang: A unit of **teletraffic**

1 Erlang = 1 user occupying 1 channel for 1 hour

Offered Traffic (A or E) =
Number of users × Average call duration per hour

Erlang B Formula

Assumptions:

- Lost calls are cleared (not retried)
- No queuing of calls
- All calls are of equal length

Formula (Erlang B):

$$B(E,N) = \frac{\frac{E^N}{N!}}{\sum_{k=0}^{N} \frac{E^k}{k!}}$$

- Where:
- E = Offered traffic in Erlangs
- N = Number of available channels
- B = Blocking probability (GoS)

```python
from math import factorial

def erlang_b(E, N):
    numerator = (E ** N) / factorial(N)
    denominator = sum((E ** k) / factorial(k) for k in range(N + 1))
    return numerator / denominator

# Given values
E = 10
N = 20

# Calculate blocking probability
blocking_prob = erlang_b(E, N)
blocking_prob_percentage = blocking_prob * 100
blocking_prob_percentage
```

Interpreting Erlang B

Channels (N)	Traffic (E)	GoS (B)
10	5 Erlangs	~1.83%
20	10 Erlangs	~0.19%
50	35 Erlangs	~0.33%

Trunking Efficiency vs. Channels

- As number of channels increases:
  - Efficiency increases
  - Blocking decreases

- Diminishing returns after a point

Improving Coverage and Capacity in Cellular Systems

Why Improve Coverage and Capacity?

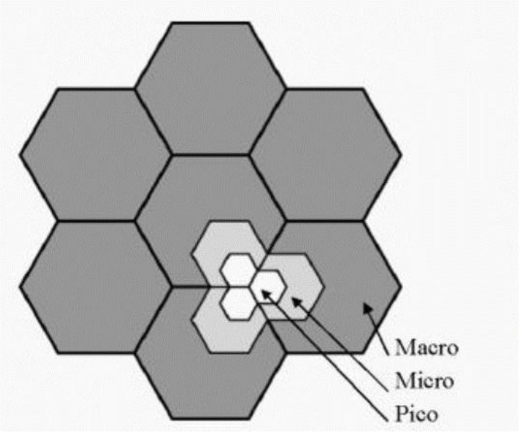
- Growing number of users
- Higher data rate demands
- More diverse use cases (voice, data, multimedia)
- Limited spectrum availability

Techniques to Improve Coverage

- Cell Splitting
- Sectoring
- Repeater Deployment
- Use of Directional Antennas
- Power Control

Cell Splitting

- Definition:
  - Subdividing a congested cell into smaller cells
  - Reduces radius →Increases number of cells →Capacity
  - Requires new base stations
  - Increases frequency reuse



Sectoring

- Divides a cell into 3 or 6 sectors
- Uses directional antennas
- Reduces co-channel interference
- Each sector covers 120° or 60°
- Improves Signal-to-Interference Ratio (SIR)

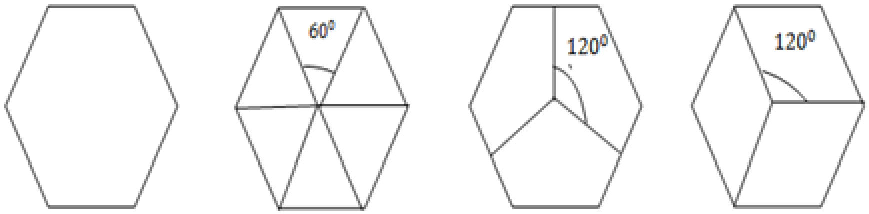


Fig: omni-directional 60^0 sectoring 120^0 sectoring

Repeaters

- Extend coverage to dead zones
- Boost signal without handoff
- Do not increase capacity
- Add noise and may cause interference

Power Control

- Minimize transmitted power
- Avoid unnecessary interference
- Maintain desired **QoS**
- Used in both uplink and downlink
- Critical in CDMA systems (to mitigate near-far problem)

Techniques to Improve Capacity

- Frequency Reuse Optimization
- Channel Borrowing
- Handoff Optimization
- Microcell Zone Concept
- Hierarchical Cell Structures (HCS)

Channel Borrowing

- Dynamic allocation of unused channels
- Borrow channels from neighboring cells
- Utilizes spectrum efficiently
- Must avoid co-channel interference

Microcell Zone Concept

- Divides a macrocell into micro-zones
- Antennas placed around cell boundary
- Controlled by a single base station
- Improves handoff
- Reduces power consumption

Hierarchical Cell Structures (HCS)

- Overlay of macrocells, microcells, picocells
- High-speed users → macrocell
- Pedestrians → microcell
- Indoor users → picocell
- Efficient user classification improves coverage & capacity

End of Chapter 4