Topic 5: Cellular System Design and Performance

<u>Content</u>:

1) The Cellular Concept
   - Cellular Structure, Frequency Reuse, etc.

2) Interference and Effects on System Performance

3) Design for Coverage
   - Number of cells required in a given coverage area

4) Design for Capacity
   - Maximum number of users supported by a Cellular system

Topic 5 Learning Outcomes

At the end of this Topic, you will be able to perform:

- Coverage design of a cellular system
- Capacity design of a cellular system

The Cellular Concept

- Divide the total service area into separate geographical regions, each referred to as a "Cell"
  - Each cell is controlled by a base station (BS)
  - Total channels in the system is divided into a number of channel groups
  - Each BS (cell) is allocated a "Channel Group" (= fraction of the total channels available for the entire system)
  - Adjacent base stations are assigned different channel groups (CGs) to minimize mutual interference between base stations
  - The group of neighboring base stations where all the available system channels are used is called a "cluster". I.e., cluster size = # of CGs
- The cellular concept results in frequency reuse

Advantage of Frequency Reuse

Fact: Frequency reuse increases cellular system capacity.

Proof:

Consider a cellular system with S duplex channels and frequency reuse plan K.

This implies: each cell is assigned a channel group of size n channels where $n = S/K$

Clearly: $n < S$ because $K > 1$

Suppose the size of the service area is N_{tot} cells.

With a frequency reuse plan K, the channel groups are replicated M times within the service area, where $M = N_{tot}/K$. Clearly: $M > 1$ because $N_{tot} > K$

Define Capacity, C as the total number of duplex channels simultaneously in use throughout the service area.

That is, $C = M * K * n = M * K * (S/K) = M * S$

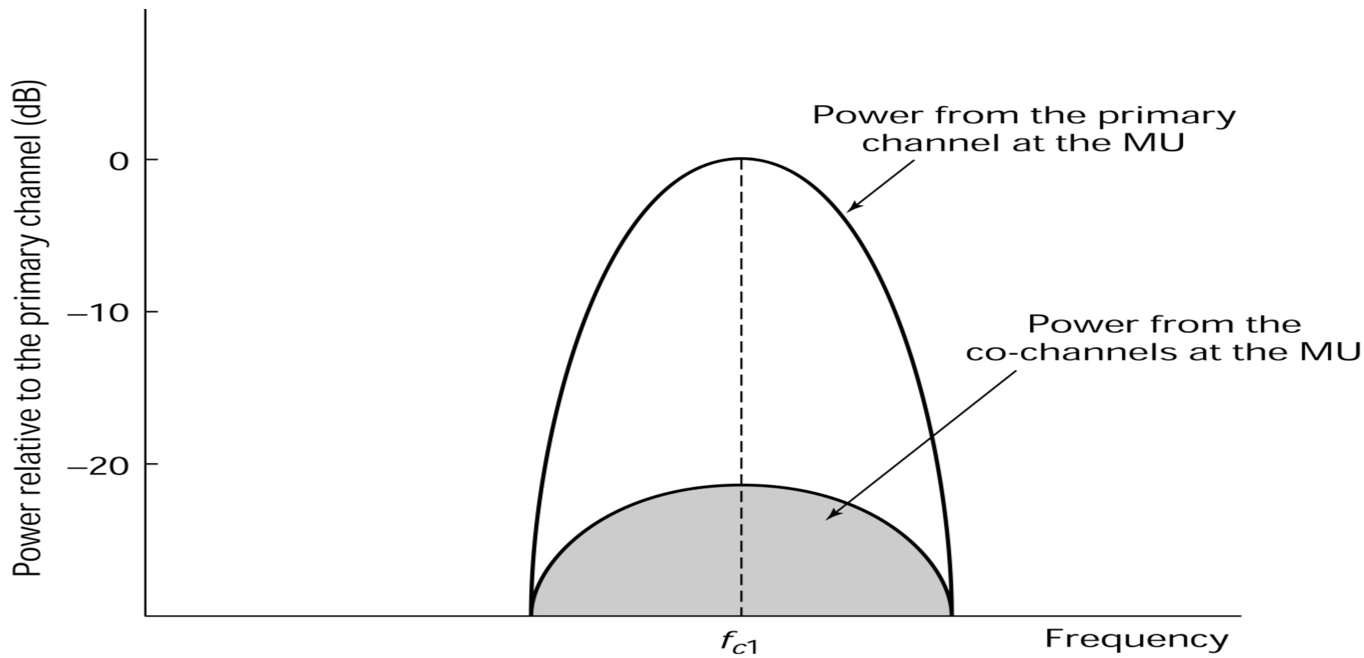
Clearly, since $M > 1$, this means $C > S$. *Conclusion #1:* frequency reuse increases capacity

Furthermore: $C = M * S = (N_{tot}/K) * S = (N_{tot} * S)/K$.

Conclusion #2: Capacity C is inversely proportional to K, the frequency reuse plan

Limitation of Frequency Reuse

- Frequency reuse results in co-channel interference, defined as the power received from the co-channels
- The severity of co-channel interference depends on the value of the reuse distance *D*. The smaller the reuse distance, the higher the co-channel interference, and vice-versa.



Quantitative Measure of Co-channel Interference: Signal-to-Interference Ratio (SIR)

Definition:

- SIR is defined as the ratio of received desired signal power, P_S to total received interference power, P_I

Analysis of SIR:

The signal-to-interference plus noise ratio, *SINR*, is defined by:

$$SINR = \frac{P_S}{P_I + N}$$

where N is thermal noise power at the receiver

If $P_I >> N$, as is the case in cellular systems, $SINR \approx SIR = P_S / P_I$

Forward link: MS is receiving interfering signal power from N_I other base stations:

$$SIR = P_S \Big/ \left(\sum_{i=1}^{N_I} P_{I,i} \right)$$

where $P_{I,i}$ is the received power from the ith interfering base station

Design for Coverage

Design Goal:

- Find the number of cells required to provide radio coverage in a given service area

Given Input Parameters and Design Requirements:

- Transmit power, P_T
- Receiver sensitivity, P_{min}
- Coverage reliability (i.e., outage probability and/or bit error rate objective)
- Distance-dependent path loss model, $\overline{PL}(d)$ (studied in Topic 2)
- Size of the service area
- Shape of the cells to be deployed in the service area

Coverage Design Methodology

Step 1: Calculate the maximum allowable path loss, $PL_{max,dB} = P_{T,dBx} - P_{min,dBx}$

Step 2: Calculate the maximum cell radius R

- 2 cases of interest: Case 1: Without coverage reliability constraint

- Set $\overline{PL}(d)_{dB} = PL_{max,dB}$ and solve for $d = R$

Case 2: With coverage reliability constraint

- Set $(\overline{PL}(d)_{dB} + M_{sh,dB} + M_{rf,dB}) = PL_{max,dB}$ and solve for $d = R$

where $M_{sh,dB}$ = shadow fading margin

$M_{rf,db}$ = small-scale (e.g., Rayleigh) fading margin

$M_{sh,dB}$ and $M_{rf,dB}$ are determined by the specified outage objectives

From Topic 2: $M_{sh,dB} = \sigma_{dB} Q^{-1}[P_{out,obj}]$; $M_{rf,dB} = 10\log[-1/(\ln(1 - P_{out,obj}))]$

Step 3: Calculate the number of cells required to cover the service area, N_{cells}

N_{cells} = Ceiling{Size of service area / Cell area}

where cell area is a function of cell radius R, and cell shape.

Class Example

Problem Statement:

A wireless system operating at 900 MHz is being planned for a large metropolitan urban city of size 10,000 km^2.

a) Find the maximum distance between the base station and a mobile station (i.e., cell radius) with no reliability constraints under a maximum allowable path loss (i.e., PL_{max}) of 160 dB . Assume the Hata model with base station antenna height h_{bs} = 100 meters and mobile station antenna height h_{ms} = 3 meters.

b) Assuming the hexagonal cell shape, how many cells are required to provide radio coverage in the service area?

c) Repeat parts a) and b) for a 99% coverage reliability objective. Assume the metropolitan area is characterized by shadow fading with $\sigma_{dB} = 6$ dB.

Design for Capacity

Capacity Design Problem 1:

- Given the number of channels provisioned and a GoS objective, find the capacity

Capacity Design Problem 2:

- Given the offered load and a GoS objective, find the number of channels required

Definitions:

Offered load: the total traffic offered (in Erlang) to the system by all the users

GoS = Grade of Service = probability of blocking

Capacity: maximum possible traffic carried (handled) by the system based on the number of channels provisioned and the GoS

Capacity in Erlang = (1 - GoS) * offered load in Erlang = Carried traffic in Erlang

Erlang: traffic unit. If call request rate is in calls per hour and average duration of calls is in hours, then traffic in Erlang = calling rate in calls per hour * average duration of calls in hours

Example: If a subscriber generates 2 calls per hour and stays on the phone for an average time of 3 minutes per call, then the traffic load in Erlang = 2 * (3/60) = 0.1 Erlang

Expression for the Probability of Blocking

ErlangB Formula:

$$GoS = P_B = \frac{\left[\frac{A^C}{C!}\right]}{\sum_{i=0}^{C} \frac{A^i}{i!}}$$

where

A: offered load (or traffic load) in Erlang

C: number of channels provisioned

P_B: probability of call blocking

- Given any two of the three parameters A, C and P_B, can find the third using the *ErlangB* formula. See Table 4.3 (pp. 158 - 159) of Course Text for ErlangB Table.

- Finally, calculate the carried traffic and channel utilization efficiency:
  - Carried traffic in Erlang, $A_c = (1 - P_B) * A$
  - Channel Utilization Efficiency, $\eta = A_c / C = \{(1 - P_B) * A\} / C =$ *trunking efficiency*

Capacity Design Goal: Maximum Number of Users Supported

__Given Input Parameters and Design Requirements:__

λ: per user call request rate in calls per hour

T_H: average duration of a call in hours

P_B: Probability of Blocking

C: Number of channels provisioned in the system

__Steps for Calculating the System Capacity:__

__Step 1:__ Calculate the offered load A (in Erlang) to the system using the ErlangB formula

__Step 2:__ Calculate the per user traffic load ρ in Erlang: $\rho = \lambda * T_H$

__Step 3:__ Calculate the system capacity = max # of users that can be supported by the system, M:

$$M = \left\lfloor \frac{A(1 - P_B)}{\lambda T_H} \right\rfloor$$

Class Example

<u>Problem Statement:</u>

Two wireless service providers, I and II, are planning to provide cellular service to an urban area. Provider I has 20 cells to cover the whole area, with each cell having 40 channels. Provider II has 30 cells, each with 30 channels. Assume that omnidirectional antennae are used in the cells and that each user makes an average of 3 calls per hour, each call lasting an average of 3 minutes.

How many users can be supported by the two providers if a GoS of 2% blocking is required?