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The Cellular Concept — System Design Fundamentals

The design objective of early mobile radio systems was to achieve a large coverage area by using a single, high powered transmitter with an antenna mounted on a tall tower. While this approach achieved very good coverage, it also meant that it was impossible to reuse those same frequencies throughout the system, since any attempts to achieve frequency reuse would result in interference. For example, the Bell mobile system in New York City in the 1970s could only support a maximum of twelve simultaneous calls over a thousand square miles [Cal88]. Faced with the fact that government regulatory agencies could not make spectrum allocations in proportion to the increasing demand for mobile services, it became imperative to restructure the radio telephone system to achieve high capacity with limited radio spectrum, while at the same time covering very large areas.

2.1 Introduction

The cellular concept was a major breakthrough in solving the problem of spectral congestion and user capacity. It offered very high capacity in a limited spectrum allocation without any major technological changes. The cellular concept is a system level idea which calls for replacing a single, high power transmitter (large cell) with many low power transmitters (small cells), each providing coverage to only a small portion of the service area. Each base station is allocated a portion of the total number of channels available to the entire system, and nearby base stations are assigned different groups of channels so that all the available channels are assigned to a relatively small number of neighboring base stations. Neighboring base stations are assigned different groups of channels so that the interference between base stations (and the mobile users

under their control) is minimized. By systematically spacing base stations and their channel groups throughout a market, the available channels are distributed throughout the geographic region and may be reused as many times as necessary, so long as the interference between co-channel stations is kept below acceptable levels.

As the demand for service increases (i.e., as more channels are needed

2.2 Frequency Reuse

Cellular radio systems rely on an intelligent allocation and reuse of channels throughout a coverage region [Oet83]. Each cellular base station is allocated a group of radio channels to be used within a small geographic area called a *cell*. Base stations in adjacent cells are assigned channel groups which contain completely different channels than neighboring cells. The base station antennas are designed to achieve the desired coverage within the particular cell. By limiting the coverage area to within the boundaries of a cell, the same group of 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. The design process of selecting and allocating channel groups for all of the cellular base stations within a system is called *frequency reuse* or *frequency planning* [Mac79].

Figure 2.1 illustrates the concept of cellular frequency reuse, where cells labeled with the same letter use the same group of channels. The frequency reuse plan is overlaid upon a map to indicate where different frequency channels are used. The hexagonal cell shape shown in Figure 2.1 is conceptual and is a simplistic model of the radio coverage for each base station, but it has been universally adopted since the hexagon permits easy and manageable analysis of a cellular system. The actual radio coverage of a cell is known as the *footprint* and is determined from field measurements or propagation prediction models. Although the real footprint is amorphous in nature, a regular cell shape is needed for systematic system design and adaptation for future growth. While it might seem natural to choose a circle to represent the coverage area of a base station, adjacent circles can not be overlaid upon a map without leaving gaps or

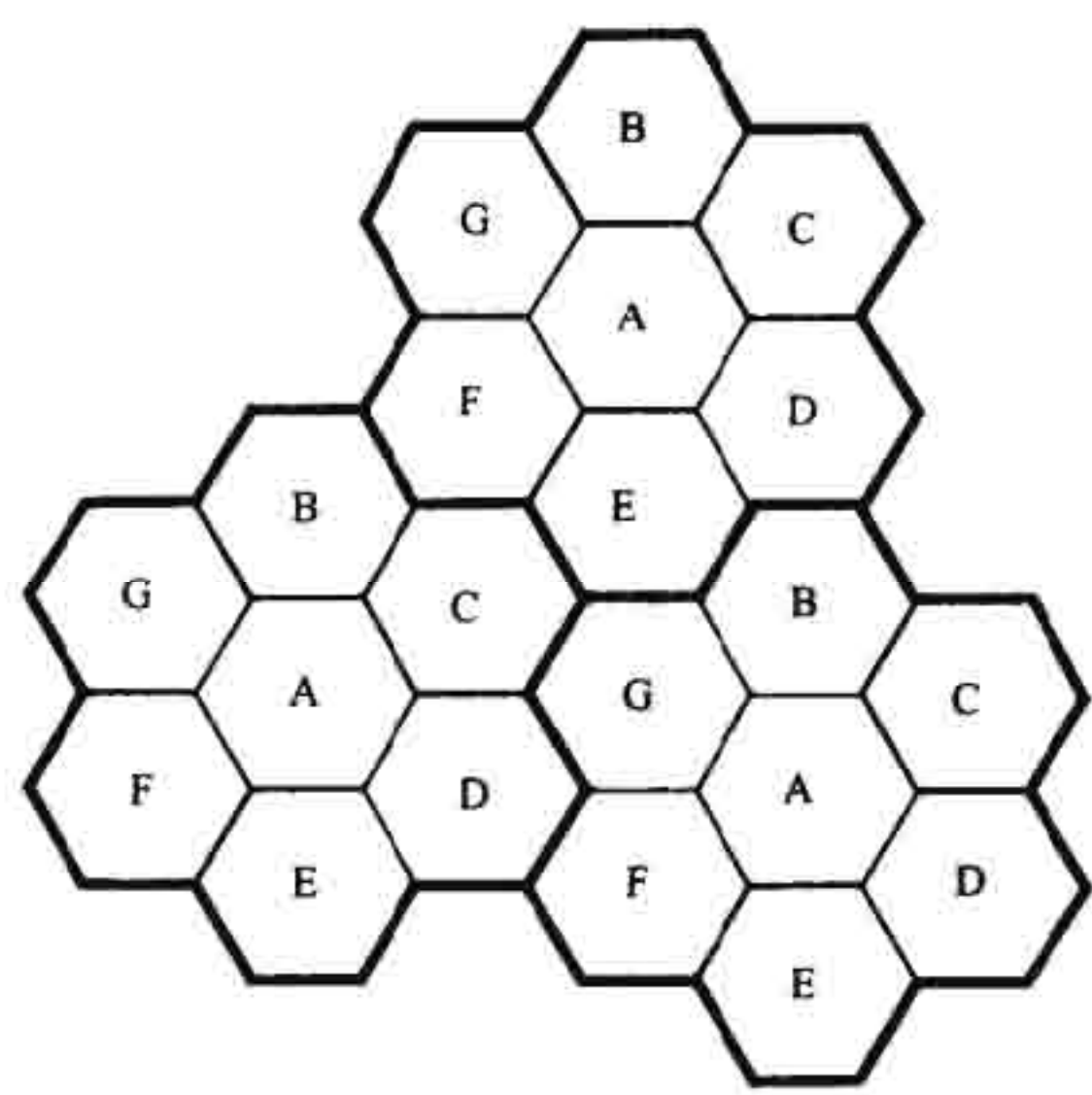


Figure 2.1
Illustration of the cellular frequency reuse concept. Cells with the same letter use the same set of channels. A cell pattern is outlined in bold and replicated over the coverage area. In this example...



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To understand the frequency reuse concept, consider a cellular system which has a total of S duplex channels available for use. If each cell is allocated a group of k channels ($k < S$), and if the S channels are divided among N cells into unique and disjoint channel groups which each have the same number of channels, the total number of available radio channels can be expressed as

$$S = kN \quad (2.1)$$

The N cells which collectively use the complete set of available frequencies is called a *cluster*. If a cluster is replicated M times within the system, the total number of duplex channels, C , can be used as a measure of capacity and is given

$$C = MkN = MS \quad (2.2)$$

As seen from equation (2.2), the capacity of a cellular system is directly proportional to the number of times a cluster is replicated in a fixed service area. The factor N is called the *cluster size* and is typically equal to 4, 7, or 12. If the cluster size N is reduced while the cell size is kept constant, more clusters are required to cover a given area and hence more capacity (a larger value of C) is achieved. A large cluster size indicates that the ratio between the cell radius and the distance between co-channel cells is large. Conversely, a small cluster size indicates that co-channel cells are located much closer together. The value for N is a function of how much interference a mobile or base station can tolerate while maintaining a sufficient quality of communications. From a design viewpoint, the smallest possible value of N is desirable in order to maximize capacity over a given coverage area (i.e., to maximize C in equation (2.2)). The *frequency reuse factor* of a cellular system is given by $1/N$, since each cell within a cluster is only assigned $1/N$ of the total available channels in the system.

Due to the fact that the hexagonal geometry of Figure 2.1 has exactly six equidistant neighbors and that the lines joining the centers of any cell and each of its neighbors are separated by multiples of 60 degrees, there are only certain cluster sizes and cell layouts which are possible [Mac79]. In order to tessellate — to connect without gaps between adjacent cells — the geometry of hexagons is such that the number of cells per cluster, N , can only have values which satisfy equation (2.3).

$$N = i^2 + ij + j^2 \quad (2.3)$$

where i and j are non-negative integers. 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. This is illustrated in Figure 2.2 for $i = 3$ and $j = 2$ (example, $N = 19$).

Example 2.1

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

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2.3 Channel Assignment Strategies

For efficient utilization of the radio spectrum, a frequency reuse scheme that is consistent with the objectives of increasing capacity and minimizing interference is required. A variety of channel assignment strategies have been developed to achieve these objectives. Channel assignment strategies can be classified as either *fixed* or *dynamic*. The choice of channel assignment strategy impacts the performance of the system, particularly as to how calls are managed when a mobile user is handed off from one cell to another [Tek91], [LiC93], [Sun94], [Rap93b].

In a fixed channel assignment strategy, each cell is allocated a predetermined set of voice channels. Any call attempt within the cell can only be served by the unused channels in that particular cell. If all the channels in that cell are occupied, the call is *blocked* and the subscriber does not receive service. Several variations of the fixed assignment strategy exist. In one approach, called the *borrowing strategy*, a cell is allowed to borrow channels from a neighboring cell if all of its own channels are already occupied. The mobile switching center (MSC) supervises such borrowing procedures and ensures that the borrowing of a channel does not disrupt or interfere with any of the calls in progress in the donor cell.

In a dynamic channel assignment strategy, voice channels are not allocated to different cells permanently. Instead, each time a call request is made, the serving base station requests a channel from the MSC. The switch then allocates a channel to the requested cell following an algorithm that takes into account the likelihood of future blocking within the cell, the frequency of use of the candidate channel, the reuse distance of the channel, and other cost functions.

Accordingly, the MSC only allocates a given frequency if that frequency is not presently in use in the cell or any other cell which falls within the minimum restricted distance of frequency reuse to avoid co-channel interference. Dynamic channel assignment reduce the likelihood of blocking, which increases the trunking capacity of the system, since all the available channels in a market are accessible to all of the cells. Dynamic channel assignment strategies require the MSC

