The Cellular Concept

Overview of Cellular Radio

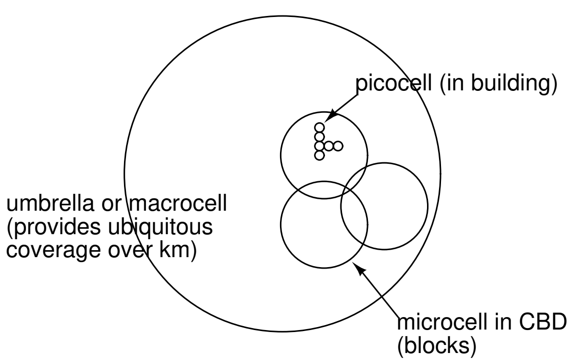
The concept of frequency reuse is what allows "cellular" systems to provide wide-area wireless phone and data services to the general population while using a limited amount of bandwidth.

A cellular system divides the geographical service area into a number of "cells". A cell provides service to users within range of a base station. The cell boundary depends on topography but the nominal cell radii in modern systems can range from 100 m to 10 km or more depending on user density.

Each cell is assigned one or more radio channels. These same channels can be reused by cells that are sufficiently far away from each other that they don't interfere. By reducing the physical sizes (radii) of the cells we can increase number of times the channels are reused within a service area and thus increase the total number of users that can be supported.

In theory this "cell-splitting" can be repeated as often as necessary to increase the number of users that can be serviced simultaneously.

However, since user density varies, using cells of only one size would be wasteful. Instead, cells of different sizes are used. Small cells (often called microcells or picocells) are used in areas with high user densities such as central business districts and shopping centers while larger cells are used in suburban and rural areas.



To allow for ubiquitous service as well as high user density, cells of different sizes are overlaid. The larger "umbrella" cells provide ubiquitous coverage while the smaller cells provide capacity in areas with high user density.

Cluster Size and Reuse Factor

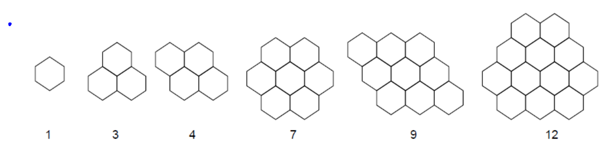
For purposes of analysis we can model cells as hexagonal areas arranged in regular groups called "clusters." Each channel is used only once within each cluster. This guarantees a certain minimum distance between cells using the same channel ("co-channel" cells).

Only some cluster sizes/patterns can be used to tessellate the coverage area (cover all the area using a regular pattern). The allowed cluster sizes are such that the cluster size, N, obeys the equation $N = i^2 + ij + j^2$ where i and j are integers.

Some possible values are:

i	j	N
0	1	1
0	2	4
0	3	9
1	1	3
1	2	7
2	2	12

and the resulting cluster shapes are:



While hexagonal cells are a useful approximation for system design, propagation conditions and site availability will determine the actual coverage areas.

To minimize infrastructure costs cell sites are typically located at the junction of the hexagonal cell boundaries. Each site covers the three adjacent cells with three 120-degree antennas.

Channel Assignment and System Capacity

In traditional cellular systems the S available channels are divided evenly among the N cells in a cluster. Thus there are $k = S/N$ channels per cell.

S is fixed because the spectrum is limited and must be shared among many users (broadcasting, non-cellular mobile services, navigation, military, ...). Therefore, one way to increase capacity within a given service area is to reduce the cell radius.

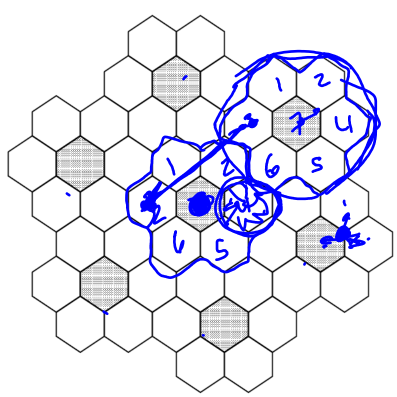
The frequency reuse factor is $1/N$ (or often just "N") and is limited by interference considerations (see below). For a fixed number of cells, a smaller N results in more channels per cell (larger k) and thus a higher capacity.

Advances in digital modulation and adaptive antennas have actually made reuse factors of $N = 1$ possible for 4G and later cellular systems.

Co-Channel Interference

The re-use factor, N, is determined by interference considerations: we must make sure that at the minimum re-use distance (determined by the cluster size and geometry) no cell will cause interference to its neighbors. The level of interference that can be tolerated depends on the type of modulation (analog, digital) and on any special techniques employed to dynamically cancel or limit this interference.

An example of potential co-channel interferers in other clusters:



Exercise 1: What is N for the example above?

In the simplest case, interference is determined by the ratio of desired to interfering signal strengths. The signal strength is determined by path loss and distance. Assuming the interference sources are uncorrelated the interference powers add and the SIR (signal to interference ratio) is:

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

where I_i is the interference power of the i'th base the forward channel).

Cell Splitting

As usage grows, a cell can be split into smaller cells using the same cluster size. The SIR will still be maintained because it is only dependent on the cluster size, not on the physical size of the cell.

Channel Assignment

Most cellular systems use fixed channel assignment. Some improvement is possible by using dynamic channel assignment where more channels can be assigned to one cell within a cluster. We still need to ensure that the minimum re-use distance is maintained.

Handoff

Mobile users may travel out of a cell. The base (and/or mobile) determines this by measuring quality of the link to current base and to adjacent bases. If another base would provide better service, a channel is allocated in that base and the mobile switches channels. This requires periodic messaging between the mobile and its allocated base.

Hysteresis is used to avoid too-frequent handovers. A "soft" handover, where a mobile receives from multiple bases (or vice-versa), is possible in some systems.

Historical Development of Cellular Systems

Cellular systems have evolved to meet increasing customer demand and to take advantage of improvements in electronic technology. Due to the high cost of replacing infrastructure and customer devices, this evolution has taken place in a sequence of discrete steps. Each such generation is also defined by one or more standards which allows for interoperability between different manufacturers. These generations are briefly described below.

Cellular systems mainly operate in two wide frequency ranges, one at around 900 MHz and another at 1.8 GHz. The exact frequencies available vary by country. Service providers are allocated frequency ranges within each band in specific geographical areas. 5G systems also use several bands in the 20–60 GHz range for short-range high-speed "millimeter-wave" links.

First-generation cellular systems applied the cellular frequency re-use concept to existing mobile telephone systems. These used FDMA and analog (FM) modulation. In North America the first-generation standard was the Advanced Mobile Phone System (AMPS) and was developed by Bell Labs. It operated at frequencies around 850 MHz and used frequency re-use factors of $N = 7$.

Second-generation cellular systems were defined by the adoption of digital modulation. There were two competing and incompatible standards. One, GSM[1] used FMDA and TDMA and was developed in Europe. The other, standardized as IS-95, used CDMA (code division multiple access) and was developed by the US company Qualcomm.

Third-generation cellular systems introduced data services and increased peak data rates. These systems used TDMA. They were also known as WCDMA ("Wideband CDMA" – not actually CDMA) and UMTS (Universal Mobile Telecommunications System). There were two variants of WCDMA that evolved from the two second-generation cellular systems (GSM and CDMA).

Fourth-generation cellular systems are defined by the use of packet switching for more efficient data service and spatial multiplexing to increase frequency re-use. The widely-adopted standard is LTE[2]. It uses OFDMA for the downlink and FDMA for the uplink.

Fifth-generation systems are being deployed by service providers. They should provide additional capacity through added spectrum, more aggressive spatial multiplexing, cooperation with unlicensed services and use of millimeter-wave frequencies for short-range high-rate links.

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[1] GSM originally stood for Group Speciale Mobile, the European study group that developed the concept.

[2] LTE stood for Long Term Evolution, presumably from WCDMA to something else.