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ECS 445: Mobile Communications
The Cellular Concept

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November 22, 2009

This note covers fundamental cellular radio concepts which are at the core of providing wireless communication service to subscribers on the move using limited radio spectrum.

Contents

1 Cellular Telephone Systems

1.1. Radio telephone system should be structured to achieve high capacity with limited radio spectrum while at the same time covering very large areas.

1.2. Older System:

- Achieve a large coverage area by using a simple, high powered transmitter.
  - Put BS on top of mountains or tall towers, so that it could provide coverage for a large area.
- The next BS was so far away that interference was not an issue.
- Severely limit the number of users that could communicate simultaneously.
- Noise-limited system with few users.
- 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.

1.3. The number of simultaneous calls a mobile wireless system can accommodate is essentially determined by the total spectral allocation for that system and the bandwidth required for transmitting signals used in handling a call.

Example 1.4. Using a typical analog system, each channel needs to have a bandwidth of around 25 kHz to enable sufficient audio quality to be carried, as well as allowing for a guard band between adjacent signals to ensure there are no undue levels of interference. Using this concept, it is possible to accommodate only forty users in a frequency band 1-MHz wide. Even if 100 MHz were allocated to the system, this would enable only 4000 users to have access to the system.

- Today cellular systems have millions of subscribers, and therefore a far more efficient method of using the available spectrum is needed.

1.5. Cellular systems accommodate a large number of users over a large geographic area, within a limited frequency spectrum.

- High capacity is achieved by limiting the coverage of each base station transmitter to a small geographic area called a ***cell*** so that the same radio channels may be reused by another base station located some distance away.
- The coverage area is divided into many cells.
- Replace a single, high power transmitter (large cell) with many low power transmitters (small cells) each providing coverage to only one cell area (a small portion of the service area).
- A sophisticated switching technique called a ***handoff*** enables a call to proceed uninterrupted when the user moves from one cell to another.

1.6. The concept of cells was first proposed as early as 1947 by Bell Laboratories in the US, with a detailed proposal for a "High-Capacity Mobile Telephone System" incorporating the cellular concept submitted by Bell Laboratories to the FCC in 1971. The first AMPS system was deployed in Chicago in 1983.

1.7. Basic cellular system

- Consist of mobile stations, base stations, and a mobile switching center (MSC).
- Mobile switching center (MSC)
  - Sometimes called a mobile telephone switching office (MTSO)
  - Coordinates the activities of all of the base stations
  - Connect the entire cellular system to the PSTN.
  - Accommodates all billing and system maintenance functions
- Each mobile communicates via radio with one of the base stations and may be handed-off to any number of base stations throughout the duration of a call.
- Mobile station
  - Contains a transceiver, an antenna, and control circuitry.
- Base stations
  - Serve as a bridge between all mobile users in the cell and connects the simultaneous mobile calls via telephone lines or microwave links to the MSC.
  - Consist of several transmitters and receivers which simultaneously handle full duplex communications
  - Generally have towers which support several transmitting and receiving antennas.

1.8. Communication between the base station and t.he mobiles is defined by a standard "common air interface (CAl)" that specifies four different channels.

(a) Forward voice channels (FVC): voice transmission from the base station to mobiles

(b) Reverse voice channels (RVC): voice transmission from mobiles to the base station

(c) Forward control channels (FCC) and reverse control channels (RCC)

- Often called setup channels
- Involve in setting up a call and moving it to an unused voice channel.
- Initiate mobile calls
- Transmit and receive data messages that carry call initiation and service requests, and are monitored by mobiles when they do not have a call in progress.
- FCCs also serve as beacons which continually broadcast all of the traffic requests for all mobiles in the system.
- Supervisory and data messages are sent in a number of ways to facilitate automatic channel changes and handoff instructions for the mobiles before and during a call.

1.9. Typically, about 5% of the entire mobile spectrum is devoted to control channels, which carry data messages that are very brief and bursty in nature, while the remaining 95% of the spectrum is dedicated to voice channels.

2 Frequency Reuse

Frequency reuse refers to the use of radio channels on the same carrier frequency to cover different areas which are separated from one another by sufficient distances so that co-channel interference is not objectionable. Frequency reuse is employed not only in mobile-telephone service but also in entertainment broadcasting and most other radio services.

2.1. Most modern wireless systems are organized into geographic cells, each controlled by a base station.

- Exceptions:
  - Small-area systems such as local-area wireless networks and personal-area networks.
  - Ad hoc and wireless sensor networks

2.2. Cellular radio systems rely on an ***intelligent allocation and reuse*** of channels throughout a coverage region

- 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 within the boundaries of a cell, the same group of channel 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 distance between two cells that an use the same frequency channels is called the ***reuse distance***.
  - This reuse distance can be computed from *link budgets*.

2.3. Why can't we use each frequency in each cell?

- Same reason as why we separate the BSs of the older system far away from one another.
- Suppose user A is at the boundary of its assigned cell, so that distances from the "useful" BS and from a neighboring BS are the same.

    - If the neighboring BS transmits in the same frequency channel (in order to communicate with user B in its own cell), then the signal-to-interference ratio (SIR) seen by user A is 0 dB.

- So, reuse a frequency not in every cell, but only in cells that have a certain minimum distance from each other.

- Using different allocated frequency bands, adjacent cells can overlap without causing interference.

2.4. We use ***hexagonal cell shape*** as a simplistic model of the radio coverage for each base station.

- 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.
    - In reality, it is not possible to define exactly the edge of a cell. The signal strength gradually reduces, and towards the edge of the cell performance falls. As the mobiles themselves also have different levels of sensitivity, this adds a further greying of the edge of the cell.
    - It is therefore impossible to have a sharp cut-off between cells. In some areas they may overlap, whereas in others there will be a "hole" in coverage.
    - Although the real footprint is amorphous in nature, a regular cell shape is needed for systematic system design and adaptation for future growth.

- Why hexagon?
    - Adjacent circles cannot be overlaid upon a map without leaving gaps or creating overlapping regions.
    - When considering geometric shapes which cover an entire region without overlap and with equal area, there are three sensible choices: a square, an equilateral triangle, and a hexagon.
    - A cell must be designed to serve the weakest mobiles within the footprint, and these are typically located at the edge of the cell.
        - For a given distance between the center of a polygon and its farthest perimeter points, the hexagon has the largest area of the three.
        - By using the hexagon geometry, the fewest number of cells can cover a geographic region
    - Closely approximate a circular radiation pattern which would occur for an omnidirectional base station antenna and free space propagation.
    - Permit easy and manageable analysis of a cellular system.

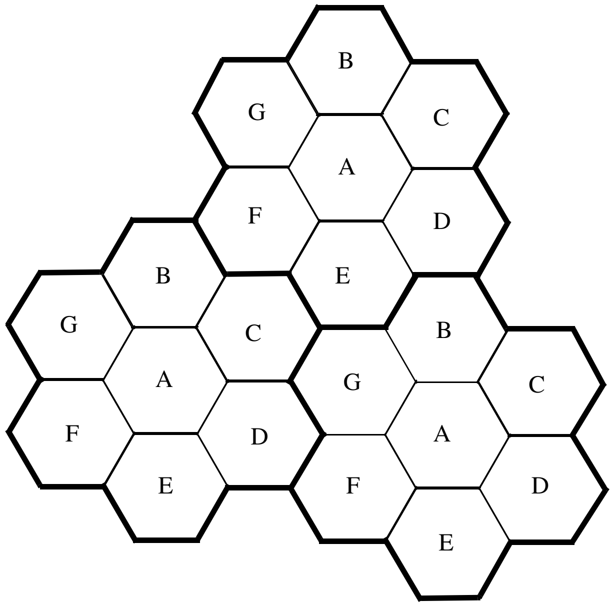

Figure 1: Illustration of the cellular frequency reuse concept. Cells with the same letter use the same set of frequencies. A cell cluster is outlined in bold and replicated over the coverage area. In this example, the cluster size, N, is equal to seven, and the frequency reuse factor is 1/7. [3, Fig 3.1]

2.5. Figure 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.

2.6. ***Cluster***

- The total coverage area is divided into clusters.
- There can be no co-channel interference within a cluster.
- The number of cells in a cluster is called the ***cluster size***. This number is denoted by N.
- The N cells collectively use the complete set of available frequencies.

2.7. Capacity

- Let
  - S = the total number of available duplex radio channels for the system
  - k = the number of channels allocated to each cell ($k < S$)
  - N = cluster size

(a) If the S channels are divided among N cells into unique and disjoint channel groups which each have the same number of channels,

$$S = kN.$$

(b) If a cluster is replicated M times within the system, the total number of duplex channels, C, is given by

$$C = MS = MkN.$$

(c) For a fixed total coverage area A_{total} and the coverage area A_{cell} of each cell, the number of cells in the system is

$$M \times N = \frac{A_{\text{total}}}{A_{\text{cell}}}.$$

In which case,

$$\boxed{C = \frac{A_{\text{total}}}{A_{\text{cell}}} \times \frac{S}{N}.}$$

- 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.
- The smallest possible value of N is desirable in order to maximize capacity over a given coverage area.
    - Small value of N may lead to large interference. This is another factor to be considered when determining the value of N.

3 Cell planing with hexagonal cells

3.1. There are only certain cluster sizes and cell layouts which are possible. The number of cells per cluster, N, can only have values which satisfy

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

where i and j are non-negative integers.

- To locate 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.
- As examples, the AMPS system uses 7; GSM uses 3 or 4.

3.2. Hexagon:

- See Figure 4.
- Area $= 6 \times 2 \times \left(\frac{1}{2} \times \frac{\sqrt{3}}{2}R \times \frac{1}{2}R\right) = \frac{3\sqrt{3}}{2}R^2 \approx 2.598R^2$

3.3. Center-to-center distance between closest co-channels (interfering cells)

$$\begin{aligned} D &= \sqrt{\left(i\sqrt{3}R\right)^2 + \left(j\sqrt{3}R\right)^2 - 2\left(i\sqrt{3}R\right)\left(j\sqrt{3}R\right)\cos\left(120^\circ\right)} \\ &= R\sqrt{3\left(i^2 + j^2 + ij\right)} = R\sqrt{3N}. \end{aligned}$$

- Also called **reuse distance**.

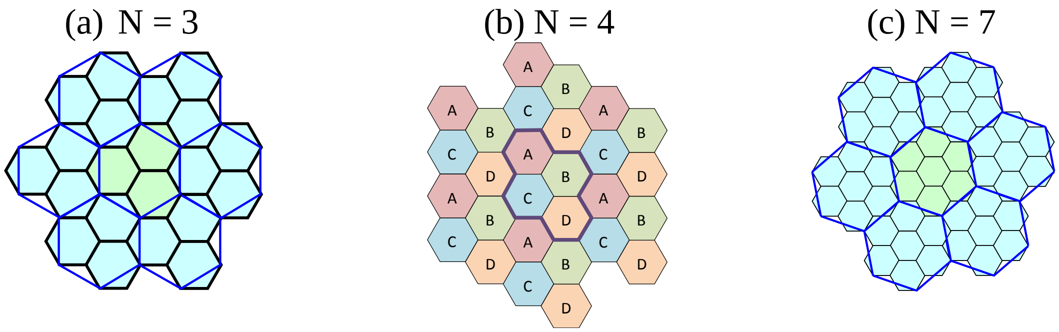

Figure 2: Example of cell layouts: (a) N = 3, (b) N = 4, and (c) N = 7.

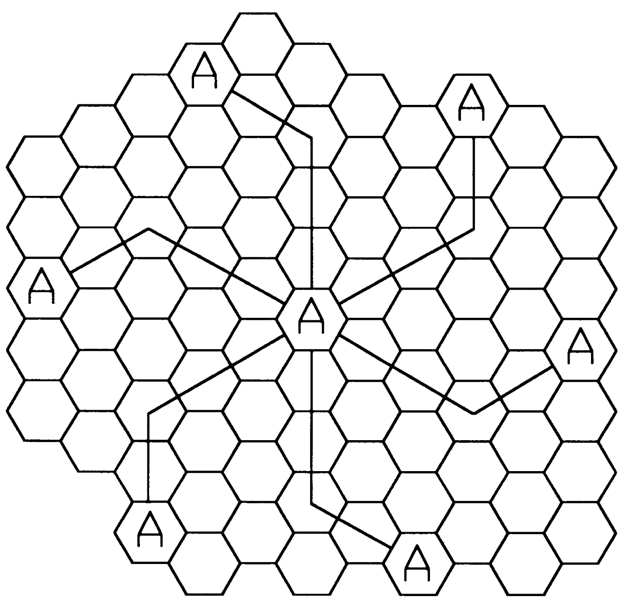

Figure 3: Method of locating co-channel cells in a cellular system. In this example, $N = 19$ (i.e., $i = 3$, $j = 2$). [3, Fig 3.2]

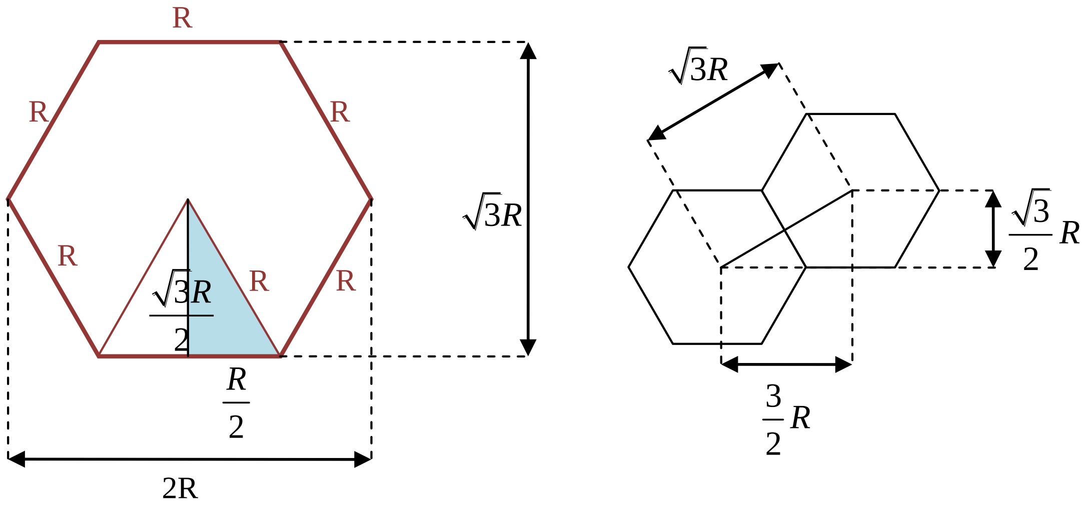

Figure 4: Hexagon

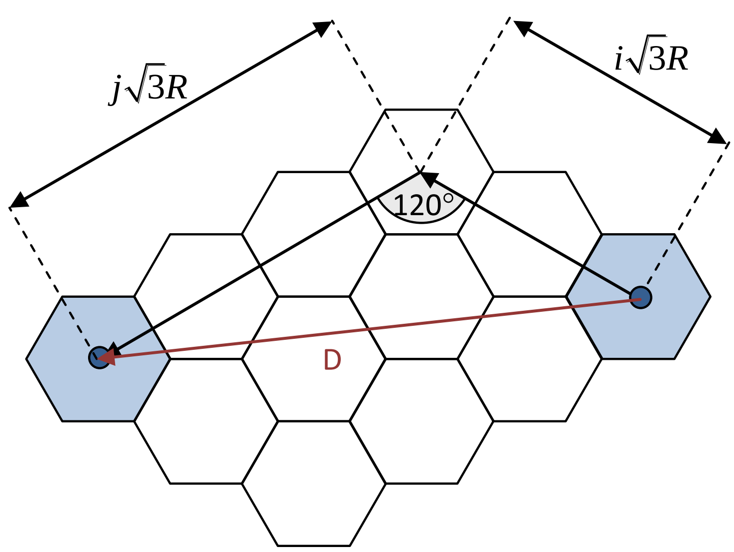

Figure 5: Finding the distance between co-channels

4 Co-Channel Interference

4.1. Interference is the major limiting factor in the performance of cellular radio systems.

- Interference has been recognized as a major bottleneck in increasing capacity and is often responsible for dropped calls.

4.2. Sources of interference include

(a) another mobile in the same cell,

(b) a call in progress in a neighboring cell,

(c) other base stations operating in the same frequency band, or

(d) any noncellular system which inadvertently leaks energy into the cellular frequency band.

4.3. Effects of interference:

- 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.

4.4. The two major types of system-generated cellular interference are **co-channel interference** and **adjacent channel interference**.

4.5. Frequency reuse and co-channel interference:

- Frequency reuse implies that in a given coverage area there are several cells that use the same set of frequencies. These cells are called **co-channel cells**, and the interference between signals from these cells is called **co-channel interference**.
- Unlike thermal noise which can be overcome by increasing the signal-to-noise ratio (SNR), co-channel interference cannot be combated by simply increasing the carrier power of a transmitter.
    - An increase in carrier transmit power increases the interference to neighboring co-channel cells.
- To reduce co-channel interference, co-channel cells must be physically separated by a minimum distance to provide sufficient isolation due to propagation.

4.6. Co-channel reuse ratio: For a hexagonal geometry

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

- By increasing Q, the spatial separation between co-channel cells relative to the coverage distance of a cell is increased. Therefore, a large value of Q improves the transmission quality, due to a smaller level of co-channel interference.

- A small value of Q provides larger capacity since the cluster size N is small.

- A trade-off must be made between these two objectives in actual cellular design.

4.7. A "tier" of cells is the collection of co-channel cells that are more-or-less the same distance away from the mobile in the serving cell.

- When a hexagonal shape is assumed, the number of co-channel cells in the tth tier of co-channel cells is $6t$, regardless of the cluster size.

4.8. SIR: Let K be the number of co-channel interfering cells. Then, the **signal-to-interference ratio (S/I or SIR)** for a mobile receiver which monitors a forward channel can be expressed as

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

where S is the desired signal power from the desired base station and I_i is the interference power caused by the ith interfering co-channel cell base station.

- This ratio is comparable with the signal-to- noise ratio used as a performance measure in non-mobile communication systems.

- The SIR should be greater than a specified threshold for proper signal operation.
    - In the first-generation AMPS system, designed for voice calls, the desired performance threshold is SIR equal to 18 dB.
    - For the second-generation digital AMPS system (D-AMPS or IS-54/136), a threshold of 14 dB is deemed suitable.
    - For the GSM system, a range of 7-12 dB, depending on the study done, is suggested as the appropriate threshold.

- Only a relatively small number of nearby interferers need be considered, because of the rapidly decreasing received power as the distance d in (1) increases.
    - In a fully equipped hexagonal-shaped cellular system, there are always six cochannel interfering cells in the first tier, as shown in Figure 6.

4.9. Propagation measurements in a mobile radio channel show that the average received signal strength at any point decays as a power law of the distance of separation between a transmitter and receiver. The average received power P_r at a distance d from the transmitting antenna is approximated by

$$P_r = P_0 \left(\frac{d}{d_0}\right)^{-\gamma} = \frac{k}{d^\gamma} \tag{1}$$

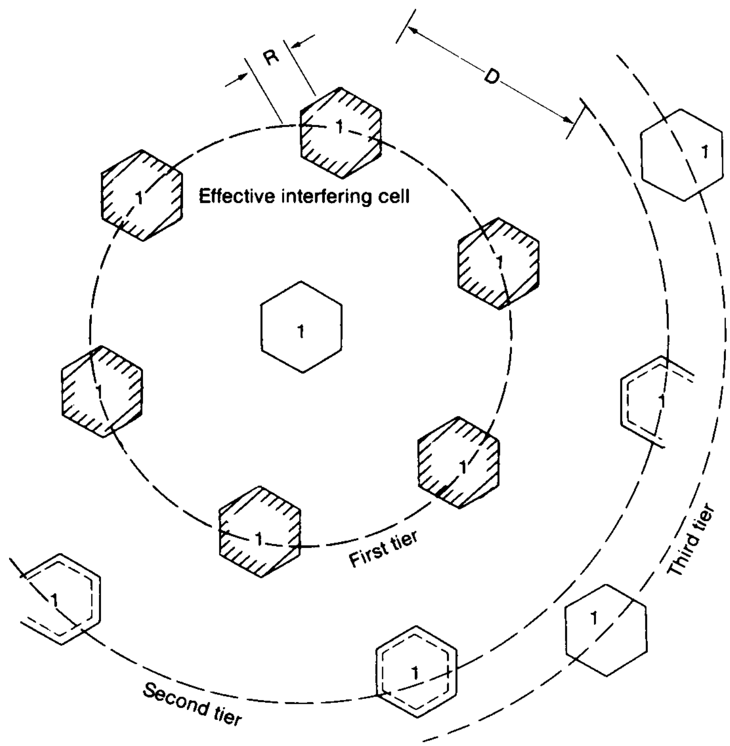

Figure 6: Six effective interfering cells of cell 1. [1, Figure 2.15]

where P_0 is the power received at a close-in reference point in the far field region of the antenna at a small distance d_0 from the transmitting antenna and γ is the **path loss exponent**.

4.10. *Approximation*: Assume

(a) Base stations are located in the centers of each cell.

(b) The transmit power of each base station is equal.

(c) Each cell transmits an independent signal, such that interfering signal powers may be added.

(d) The path loss exponent is the same throughout the coverage area.

(e) All K interfering (co-channel) base stations are equidistant from the desired base station and this distance is equal to the co-channel distance D.

(f) For the worst-case SIR calculation, let the mobile be placed at a corner of the cell.

We get

$$\frac{S}{I} = \frac{kR^{-\gamma}}{K \times (kD^{-\gamma})} = \frac{1}{K}\left(\frac{D}{R}\right)^{\gamma} = \frac{1}{K}\left(\sqrt{3N}\right)^{\gamma}. \tag{2}$$

- As N increase, increasing D/R, this approximation become more accurate.

5 Trunking

5.1. Trunking

- Allow a large number of users to share the relatively small number of channels in a cell by providing access to each user, on demand, from a pool of available channels.
- Exploit the statistical behavior of users
- Each user is allocated a channel on a per call basis, and upon termination of the call, the previously occupied channel is immediately returned to the pool of available channels.

5.2. To design trunked radio systems that can handle a specific capacity at a specific "grade of service," it is essential to understand **trunking theory** and **queuing theory**.

- The fundamentals of trunking theory were developed by Erlang, a Danish mathematician who, in the late 19th century
- Today, the measure of traffic intensity bears his name.

5.3. Definitions of Common Terms Used in Trunking Theory

- **Blocked Call**: Call which cannot be completed at time of request, due to congestion. Also referred to as a **lost call**.
- **Holding Time**: Average duration of a typical call. Denoted by $H = 1/\mu$.
- **Traffic Intensity**: Measure of channel time utilization, which is the average channel occupancy measured in Erlangs.
  - This is a dimensionless quantity and may be used to measure the time utilization of single or multiple channels.
  - Denoted by A.
- **Load**: Traffic intensity across the entire trunked radio system, measured in Erlangs.
- **Grade of Service (GOS)**: A measure of congestion which is specified as the probability of a call being blocked (for Erlang B).
  - The AMPS cellular system is designed for a GOS of 2% blocking. This implies that the channel allocations for cell sites are designed so that 2 out of 100 calls will be blocked due to channel occupancy during the busiest hour.
- **Request Rate**: The average number of call requests per unit time. Denoted by λ.

5.4. There are two types of trunked systems which are commonly used.

(a) Blocked calls cleared.

(b) Blocked calls delayed

5.5. M/M/m/m Queue Assumption: We will assume blocked calls cleared trunking with several further assumptions.

- Blocked calls cleared
  - Offers no queuing for call requests.
  - For every user who requests service, it is assumed there is no setup time and the user is given immediate access to a channel if one is available.
  - If no channels are available, the requesting user is blocked without access and is free to try again later.
- Call arrive as determined by a Poisson distribution.
- There are memoryless arrivals of requests, implying that all users, including blocked users, may request a channel at any time.
- There are an infinite number of users (with finite overall request rate).
  - Remark: While it is possible to model trunked systems with finite users, the resulting expressions are much more complicated than the Erlang B result below. Furthermore, the Erlang B formula provides a conservative estimate of the GOS, as the finite user results always predict a smaller likelihood of blocking.
- The duration of the time that a user occupies a channel is exponentially distributed, so that longer calls are less likely to occur.
- There are m channels available in the trunking pool.

5.6. Erlang B formula:

- C = the number of trunked channels offered by a trunked radio system
- A = the total offered traffic.
- The probability that a call is blocked is

$$P_b = \frac{\frac{A^C}{C!}}{\sum_{k=0}^{C} \frac{A^k}{k!}}.$$

One Erlang represents the amount of traffic intensity carried by a channel that is completely occupied

6 Improving Coverage and Capacity

As the demand for wireless service increases, the number of channels assigned to a cell eventually becomes insufficient to support the required number of users. At this point, cellular design techniques are needed to provide more channels per unit coverage area.

6.1. Techniques such as cell splitting, sectoring, and coverage zone approaches are used in practice to expand the capacity of cellular systems. Cell splitting allows an orderly growth of the cellular system.

6.2. Cell splitting allows an orderly growth of the cellular system.

- Cell splitting is the process of subdividing a congested cell into smaller cells (called **microcells**), each with its own base station and a corresponding reduction in antenna height and transmitter power.
- Cell splitting increases the capacity of a cellular system since it increases the number of times that channels are reused.
  - Essentially, achieve capacity improvement by rescaling the system.

6.3. Sectoring uses directional antennas to further control the interference and frequency reuse of channels.

- Replace a single omnidirectional antenna at the base station by several directional antennas, each radiating within a specified sector.
- The channels used in a particular cell are broken down into sectored groups and are used only within a particular sector.
- The SIR is improved. In practice, the enable planners to reduce the cluster size (N).
- The factor by which the co-channel interference is reduced depends on the amount of sectoring used. A cell is normally partitioned into three 120° sectors or six 60° sectors as shown in Figure 7(a) and (b).
- Example:
  - Assuming seven-cell reuse, for the case of 120° sectors, the number of interferers in the first tier is reduced from six to two.
  -
- Disadvantages
  - Increase number of antennas at each base station.
  - Decrease trunking efficiency due to channel sectoring at the base station. The available channels in the cell must be subdivided and dedicated to a specific antenna.
  - Number of handoffs increases because sectoring reduces the coverage area of a particular group of channels.
    - Fortunately, many modern base stations support sectorization and allow mobiles to be handed off from sector to sector within the same cell without intervention from the MSC, so the handoff problem is often not a major concern.

◦ In dense urban areas, the directional antenna patterns are somewhat ineffective in controlling radio propagation.

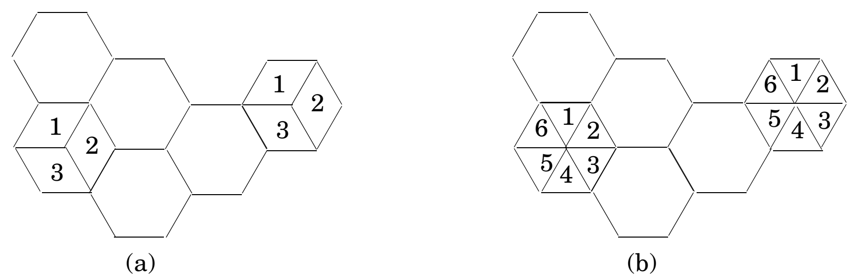

Figure 7: (a) 120 deg sectoring; (b) 60 deg sectoring.

6.4. The zone microcell concept distributes the coverage of a cell and extends the cell boundary to hard-to-reach places.

6.5. Comparison:

(a) While cell splitting increases the number of base stations in order to increase capacity, sectoring and zone microcells rely on base station antenna placements to improve capacity by reducing co-channel interference.

(b) Cell splitting and zone microcell techniques do not suffer the trunking inefficiencies experienced by sectored cells, and enable the base station to oversee all handoff chores related to the microcells, thus reducing the computational load at the MSC.

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