Chapter

7

Types of Noncochannel Interference

7.1 Subjective Test versus Objective Test

Voice quality often cannot be measured by objective testing using parameters such as the carrier-to-noise ratio C/N, the carrier-to-interference ratio C/I, the baseband signal-to-noise S/N, and the signal to noise and distortion ratio (SINAD). In a mobile radio environment, multipath fading plus variable vehicular speed are the major factors causing deterioration of voice quality.

Only the following methods can help to correct this imbalance.

1. Let the received carrier level be high to increase the signal level.
2. Let the receiver sensitivity be high to lower the noise level.
3. Maintain a low distortion level in the receiver to increase SINAD.
4. Use a diversity receiver to reduce the fading.
5. Use a good system design in a mobile radio environment and a good adjacent-channel rejection to reduce the interference.

However, when a transceiver is deployed in a mobile radio environment, a subjective test is still the only way to test this receiver, using different types of modulation, such as single-sideband, double-sideband, amplitude, and frequency modulation (SSB, DSB, AM, FM).

7.1.1 The subjective test

A subjective test can be set up according to the criterion that 75 percent of the customers perceive the voice quality at a given C/N as being "good" or "excellent," the top two levels among the five circuit-merit (CM) grades.[1] The simulator of this test must be adjusted for different mobile speeds. The customers can hear different S/N levels at the baseband on the basis of the carrier-to-noise ratio C/N being changed at the RF transmitter. One typical set of curves from the customers' perception at a mobile speed at 25 km/h (or 16 mi/h) and one at 56 km/h (or 35 mi/h) are shown[2] in Fig. 7.1. Average all the test records for different vehicle speeds and determine a C/N which can satisfy the criterion we have established.

7.1.2 The objective test

There are many objective tests at the baseband for both voice and data. The characterization of voice quality is very difficult, as mentioned previously, but evaluation of data transmission is easy. There are two major terms, bit-error rates and word error rates. The bit-error rate (BER) is the first-order statistic (independent of time or vehicle speed), and the word-error rate (WER) is the second-order statistic which is affected by the vehicle speed. These rates are discussed in Chap. 12.

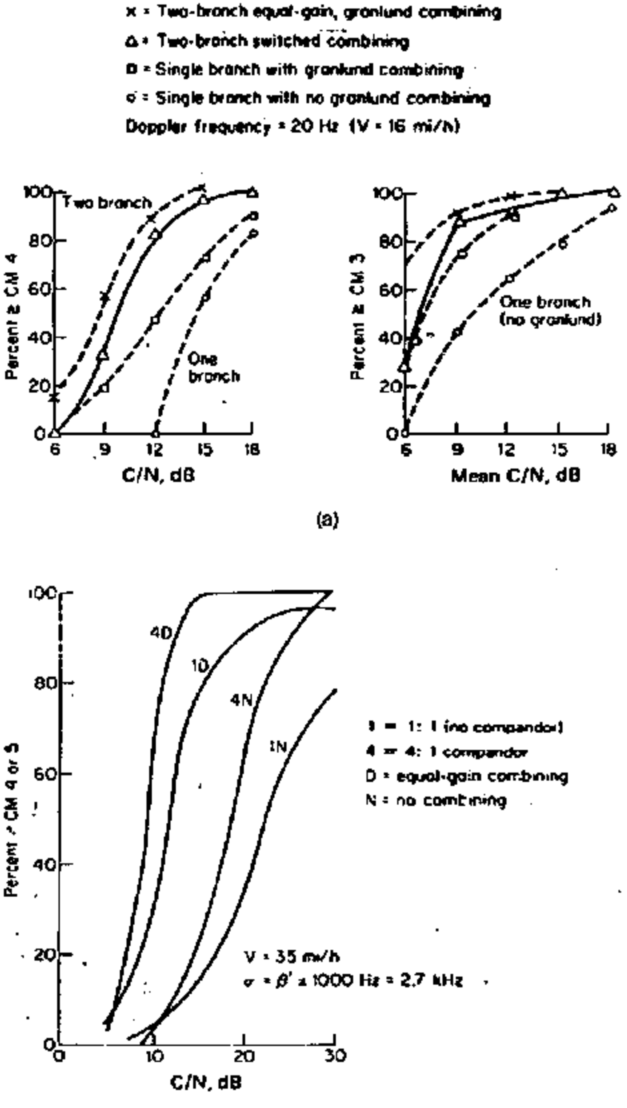
7.1.3 Measurement of SINAD

SINAD has been used as a measurement of communication signal quality at the baseband or in the cellular mobile receiver to measure the effective FM receiver sensitivity.[3] Some telephone industries use a "notched noise" measurement, in which a 1000-Hz tone is sent down the telephone line. The line noise is added onto the tone when it is received. By notching out the tone frequency, we can determine the remaining noise. This is a type of SINAD measurement.

1. The SINAD of the baseband output signal is defined as the ratio of the total output power to the power of the noise plus distortion only.

$$\begin{aligned}\text{SINAD} &= \frac{\text{total output power}}{\text{nonsignal portion}} \\ &= \frac{\text{signal + noise + distortion}}{\text{noise + distortion}} \qquad (7.1\text{-}1)\end{aligned}$$

The output power can be obtained by measuring the output from a voltmeter and then squaring the voltage, or directly from a power



(a)

(b)

Figure 7.1 Results from subjective tests. (*Reprinted from W. C. Y. Lee, Mobile Communications Engineering, McGraw-Hill Book Co., 1982, pp. 428–429.*) (*a*) System-versus-performance comparison based on circuit merit CM4 vs. CM3. (*b*) System-versus-performance comparisons based on circuit merit CM4 and CM5.

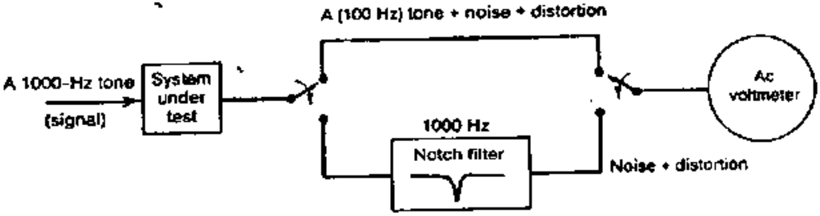


Figure 7.2 A SINAD meter.

meter. In cellular radio equipment, an input of −116 dBm is equivalent to a SINAD of 12 dB.

2. A high signal level can be measured by

$$\text{SINAD} = \frac{\text{signal} + \text{noise}}{\text{noise}} \approx \frac{\text{signal}}{\text{noise}}$$

The SINAD shown in Fig. 7.2 can be obtained by measuring the signal at the upper position and measuring the noise reading received at the lower position, assuming that the distortion is insignificant.

3. Receiver sensitivity can be measured by modulating with a 1-kHz tone at 3-kHz peak modulation deviation as shown in Fig. 7.3. The signal-generated attenuator should be adjusted until the SINAD meter shows 12 dB. Then the microvolt output is read from the attenuator dial, which reveals the "12 dB" of SINAD "sensitivity" of the receiver. This means that the signal input must be of a certain level for the signal at the output to be 12 dB higher than noise plus distortion. If the receiver noise is higher, the minimum input signal level should also be higher in order to maintain the 12-dB SINAD.

4. Noise voltage can be measured from a c-message weighting filter on any kind of telephone circuit. The frequency response of this c-message weighting filter is based on the human voice. The noise measured at the output of the filter is the noise withholding in the speech frequency spectrum. Therefore telephone line performance is measured by the amount of noise voltage through the c-message-weight filter.

Figure 7.3 Measuring receiver sensitivity.

5. The SINAD meter also can be used as a distortion meter if the noise is very low in comparison to the distortion. The SINAD meter can be used to check the maximum distortion figures of the receiver. The input signal level is increased until no thermal noise can be heard; the receiver volume meter reads the audio power, and the SINAD meter reads the distortion.

7.2 Adjacent-Channel Interference

The scheme discussed in Chap. 6 for reduction of cochannel interference can be used to reduce adjacent-channel interference. However, the reverse argument is not valid here. In addition, adjacent-channel interference can be eliminated on the basis of the channel assignment, the filter characteristics, and the reduction of near-end–far-end (ratio) interference. "Adjacent-channel interference" is a broad term. It includes next-channel (the channel next to the operating channel) interference and neighboring-channel (more than one channel away from the operating channel) interference. Adjacent-channel interference can be reduced by the frequency assignment.

7.2.1 Next-channel interference

Next-channel interference affecting a particular mobile unit cannot be caused by transmitters in the common cell site, but must originate at several other cell sites. This is because any channel combiner at the cell site must combine the selected channels, normally 21 channels (630 kHz) away, or at least 8 or 10 channels away from the desired one. Therefore, next-channel interference will arrive at the mobile unit from other cell sites if the system is not designed properly. Also, a mobile unit initiating a call on a control channel in a cell may cause interference with the next control channel at another cell site. The methods for reducing this next-channel interference use the receiving end. The channel filter characteristics[4] are a 6 dB/oct slope in the voice band and a 24 dB/oct falloff outside the voice-band region (see Fig. 7.4). If the next-channel signal is stronger than 24 dB, it will interfere with the desired signal. The filter with a sharp falloff slope can help to reduce all the adjacent-channel interference, including the next-channel interference.

7.2.2 Neighboring-channel interference

The channels which are several channels away from the next channel will cause interference with the desired signal. Usually, a fixed set of serving channels is assigned to each cell site. If all the channels are

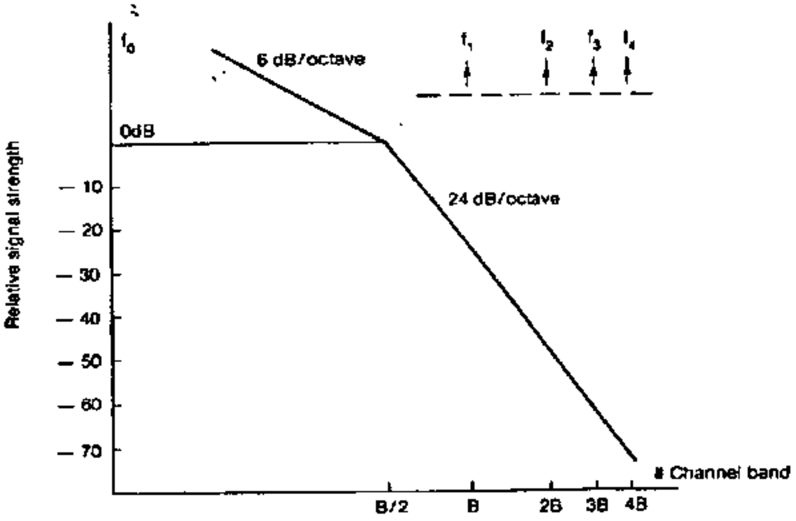


Figure 7.4 Characteristics of channel-band filter.

simultaneously transmitted at one cell-site antenna, a sufficient amount of band isolation between channels is required for a multichannel combiner (see Sec. 7.7.1) to reduce intermodulation products. This requirement is no different from other nonmobile radio systems. Assume that band separation requirements can be resolved, for example, by using multiple antennas instead of one antenna at the cell site. What channel separation would be needed to avoid adjacent-channel interference? (See Sec. 8.1.)

Another type of adjacent-channel interference is unique to the mobile radio system. In the mobile radio system, most mobile units are in motion simultaneously. Their relative positions change from time to time. In principle, the optimum channel assignments that avoid adjacent-channel interference must also change from time to time. One unique station that causes adjacent-channel interference in mobile radio systems is described in the next section.

7.3 Near-End–Far-End Interference

7.3.1 In one cell

Because motor vehicles in a given cell are usually moving, some mobile units are close to the cell site and some are not. The close-in mobile unit has a strong signal which causes adjacent-channel inter-

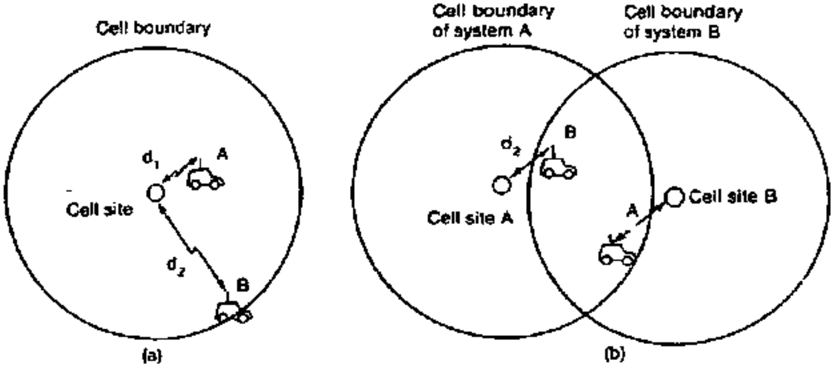


Figure 7.5 Near-end–far-end (ratio) interference. (*a*) In one cell; (*b*) in two-system cells.

ference (see Fig. 7.5*a*). In this situation, near-end–far-end interference can occur only at the reception point in the cell site.

If a separation of $5B$ (five channel bandwidths) is needed for two adjacent channels in a cell in order to avoid the near-end–far-end interference, it is then implied that a minimum separation of $5B$ is required between each adjacent channel used with one cell.

Because the total frequency channels are distributed in a set of N cells, each cell only has $1/N$ of the total frequency channels. We denote $\{F_1\}$, $\{F_2\}$, $\{F_3\}$, $\{F_4\}$ for the sets of frequency channels assigned in their corresponding cells C_1, C_2, C_3, C_4.

The issue here is how can we construct a good frequency management chart to assign the N sets of frequency channels properly and thus avoid the problems indicated above. The following section addresses how cellular system engineers solve this problem in two different systems.

7.3.2 In cells of two systems

Adjacent-channel interference can occur between two systems in a duopoly-market system. In this situation, adjacent-channel interference can occur at both the cell site and the mobile unit.

For instance, mobile unit A can be located at the boundary of its own home cell A in system A but very close to cell B of system B as shown in Fig. 7.5*b*. The other situation would occur if mobile unit B were at the boundary of cell B of system B but very close to cell A of system A. Following the definition of near-end–far-end interference given in Sec. 7.3.1, the solid arrow indicates that interference may occur at cell site A and the dotted arrow indicates that interference

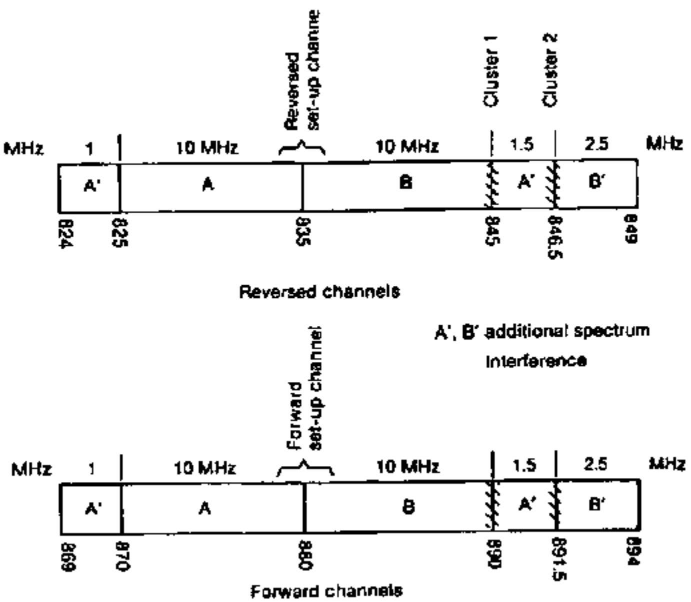


Figure 7.6 Spectrum allocation with new additional spectrum.

may occur at mobile unit A. Of course, the same interference will be introduced at cell site B and mobile unit B.

Thus, the frequency channels of both cells of the two systems must be coordinated in the neighborhood of the two-system frequency bands. This phenomenon will be of greater concern in the future, as indicated in the additional frequency-spectrum allocation charts in Fig. 7.6.

The two causes of near-end–far-end interference of concern here are

1. *Interference caused on the set-up channels.* Two systems try to avoid using the neighborhood of the set-up channels as shown in Fig. 7.6.
2. *Interference caused on the voice channels.* There are two clusters of frequency sets as shown in Fig. 7.6 which may cause adjacent-channel interference and should be avoided. The cluster can consist of 4 to 5 channels on each side of each system, that is, 8 to 10 channels in each cluster. The channel separation can be based on two assumptions.
   a. *Received interference at the mobile unit.* The mobile unit is located away from its own cell site but only 0.25 mi away from the cell site of another system.

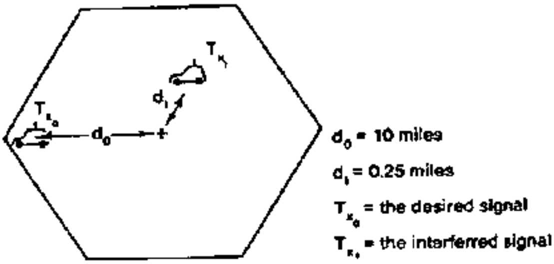


Figure 7.7 Near-end–far-end ratio interference.

b. *Received interference at the cell site.* The cell site is located 10 mi away from its own mobile unit but only 0.25 mi from the mobile unit of another system.

These assumptions are discussed in the next section. If the two system operators do not agree to coordinate their use of frequency channels and some of the cell sites of system B are at the coverage boundaries of the cells of system A, then the two groups of frequencies shown in Fig. 7.6 must not be used if interference has to be avoided. Of course, if the two systems do coordinate their use of frequency channels, adjacent channels in the two clusters can be used with no interference.

These observations regarding adjacent-channel interference lead the author to conclude that the existence of two systems having all colocation cell sites in a city is desirable since near-end–far-end ratio interference might be easy to control or might not occur if frequency channel use is coordinated.

7.4 Effect on Near-End Mobile Units

7.4.1 Avoidance of near-end–far-end interference

The near-end mobile units are the mobile units which are located very close to the cell site. These mobile units transmit with the same power as the mobile units which are far away from the cell site. The situation described below is illustrated in Fig. 7.7. The distance d_0 between a calling mobile transmitter and a base-station receiver is much larger than the distance d_I between a mobile transmitter causing interference and the same base-station receiver. Therefore, the transmitter of the mobile unit causing interference is close enough to override the desired base-station signal.[5] This interference, which is based on the distance ratio, can be expressed as

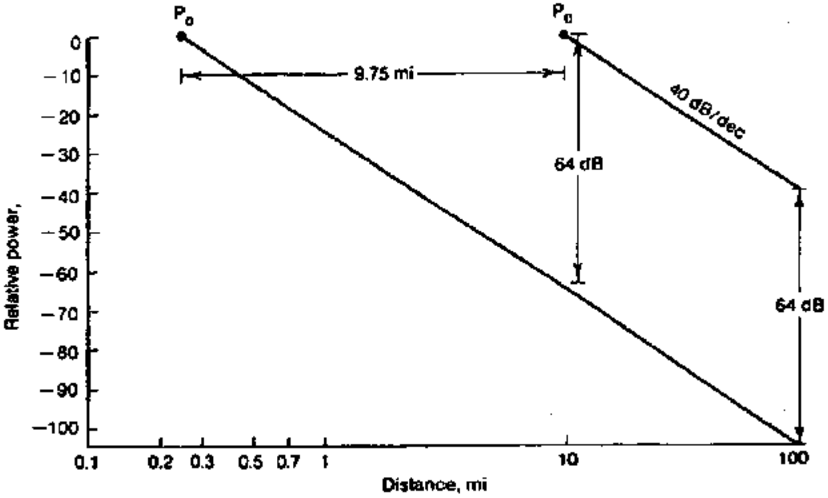


Figure 7.8 Using spacing for cochannel isolation.

$$\frac{C}{I} = \left(\frac{d_0}{d_I}\right)^{-\gamma} \tag{7.4-1}$$

where γ is the path-loss slope. The ratio d_I / d_0 is the near-end–far-end ratio. From Eq. (7.4-1) the effect of the near-end–far-end ratio on the carrier–adjacent-channel interference ratio is dependent on the relative positions of the moving mobile units.

For example, if the calling mobile unit is 10 mi away from the base-station receiver and the mobile unit causing the interference is 0.25 mi away from the base-station receiver, then the carrier-to-interference ratio for interference received at the base-station receiver with $\gamma = 4$ is

$$\frac{C}{I} = \left(\frac{d_0}{d_I}\right)^{-4} = (40)^{-4} = -64 \text{ dB} \tag{7.4-2}$$

This means that the interference is stronger than the desired signal by 64 dB (see Fig. 7.8).

This kind of interference can be reduced only by frequency separation with narrow filter characteristics. Assume that a filter of channel B has a 24 dB/oct slope;[4] then a 24-dB loss begins at the edge of the channel $B/2$. The increase from $B/2$ to B results in 24-dB loss, the increase from B to $2B$ results in another 24-dB loss, and so forth.

In order to achieve a loss of 64 dB, we may have to double the frequency band more than two times as

$$\frac{64}{L} = \frac{64}{24} = 2.67$$

where L is the filter characteristic. The frequency band separation for 64-dB isolation is

$$2^{-(C/I)/L}\left(\frac{B}{2}\right) = 2^{2.67}\left(\frac{B}{2}\right) = 3.18B \tag{7.4-3}$$

Therefore, a minimum separation of four channels is needed to satisfy the isolation criterion of 64 dB. The general formula for the required channel separation is based on the filter characteristic L, which is expressed as follows.[5]

$$\text{Frequency band separation} = 2^{G-1}B \tag{7.4-4}$$

where

$$G = \frac{\gamma \log_{10}\left(\dfrac{d_0}{d_I}\right)}{L} \tag{7.4-5}$$

7.4.2 Nonlinear amplification

When the near-end mobile unit is close to the cell site, its transmitted power is too strong and saturates the IF log amplifier if the received signal at the cell site exceeds −55 dBm. A typical log IF amplifier characteristic is shown in Fig. 7.9. Assume that the mobile unit transmitted power is 36 dBm and the antenna gain is 2 dBi. The power plus the gain is 38 dBm. The receiver power is −55 dBm at the cell cite.

The propagation loss $L = 38\text{ dBm} - (-55\text{ dBm}) = 93\text{ dB}$. We may calculate the free-space path loss, which is the maximum distance within which the saturation of the IF amplifier will occur. The calculation of free-space loss versus distance at 850 MHz is as follows.

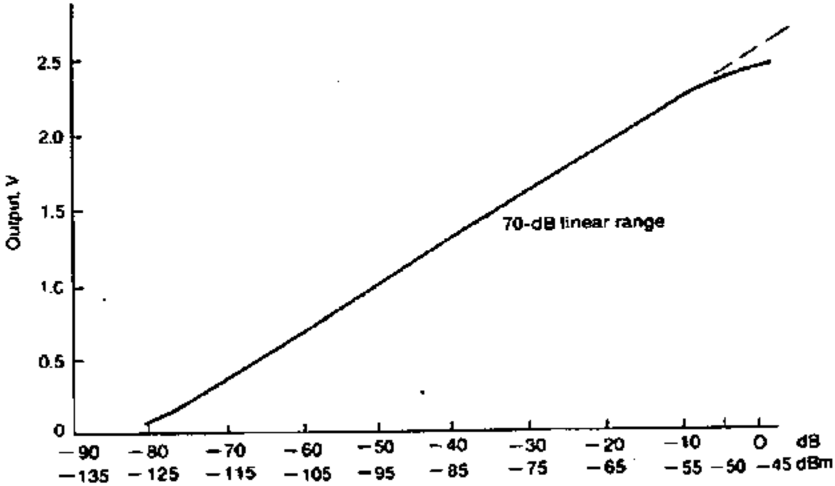


Figure 7.9 A typical intermediate-frequency log amplifier.

$$-55 \text{ dBm} = 10 \log \frac{P}{(4\pi)^2(d/\lambda)^2}$$

$$= 38 \text{ dBm} - 20 \log 4\pi - 20 \log \left(\frac{d}{\lambda}\right)$$

$$20 \log_{10} \left(\frac{d}{\lambda}\right) = 55 + 38 - 22 = 71 \tag{7.4-6}$$

$$\frac{d}{\lambda} = 10^{71/20} = 3548$$

$$d = 3548\lambda = 4115 \text{ ft}$$

$$= 1241 \text{ m} = 1.24 \text{ km}$$

This means that when the mobile unit is within 1.24 km of the cell-site boundary, it is possible to saturate the IF amplifier, and it is likely that intermodulation will be generated because of the nonlinear portion of the characteristics. If the intermodulation (IM) product matches the frequency channel of another mobile unit far away from the cell site where reception is weak, then the IM can interfere with the other frequency received at the cell site.

Therefore, the near-end mobile unit can cause interference at the cell site with the far-end mobile unit by generating IM at the cell-site amplifier and by leaking into the signal of the far-end mobile unit received at the cell site.

7.5 Cross Talk—A Unique Characteristic of Voice Channels

When the cellular radio system was designed, the system was intended to function like a telephone wire line. A wire pair serves both directions of traffic at the line transmission. In a mobile cellular system there is a pair of frequencies, occupying a bandwidth of 60 kHz, which we simply call a "channel." A frequency of 30 kHz serves a received path, and the other 30 kHz accommodates a transmitted path.

Because of paired-frequency (as a wire pair) coupling through the two-wire–four-wire hybrid circuitry at the telephone central office, it is possible to hear voices in both frequencies (in the frequency pair) simultaneously while scanning on only one frequency in the air. Therefore, just as with a wire telephone line, the full conversation can be heard on a single frequency (either one of the two). This phenomenon does not annoy cellular mobile users; when they talk they also listen to themselves through the phone receiver. They are not even aware that they are listening to their own voices.

This unnoticeable cross-talk phenomenon in frequency pairs has no major impact on both wire telephone line and cellular mobile performance. But when real cross talk occurs it has a larger impact on the cellular mobile system than on the telephone line, because the amount of cross talk could potentially be doubled since cross talk occurring on one frequency will be heard on the other (paired) frequency. Cross talk occurring on the reverse voice channel can be heard on the forward voice channel, and cross talk occurring on the forward voice channel can be heard on the reverse channel. Therefore, the cross-talk effect is twofold. A number of situations are conducive to cross talk.

Near-end mobile unit. Cross talk can occur when one mobile unit (unit A) is very close to the cell site and the other (unit B) is far from the cell site. Both units are calling to their land-line parties as shown in Fig. 7.10. The near-end mobile unit has a strong signal such that the demultiplexer cannot have an isolation (separation) of more than 30 dB. Then the strong signal can generate strong cross talk while the received signal from mobile unit B is 30 dB weaker than signal A.

Near-end mobile units can belong to one system or to another (foreign) system. If the foreign system units are operating in the new allocated spectrum channels, cross talk can occur. When the mobile

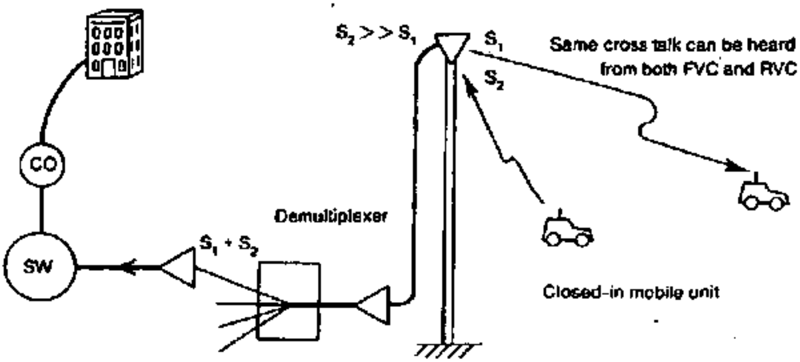


Figure 7.10 Cross-talk phenomenon.

unit is close to the cell site and the cell site is capable of reducing the power of the mobile unit, the near-end mobile interference can be reduced.

If the operating frequencies of both home system units and foreign system units are in the new allocated spectrum channels and the isolation of the multicoupler (demultiplexer) could be only 30 dB, cross talk would occur in the two interfering clusters of channels (Fig. 7.6) and could not be controlled by the system operator.

Close-in mobile units. When a mobile unit is very close to the cell site and if the reception at the cell site is greater than −55 dBm, the channel preamplifier at the cell site can become saturated and produce IM as a result of the nonlinear portion of the amplification. These IM products are the spurious (unwanted frequency) signal which leaks into the desired signal and produces cross talk. Also, as mentioned previously, the same cross talk can be heard from both the forward and reverse voice channels.

Cochannel cross talk. The cochannel interference reduction ratio q should be as large as possible to compensate for the cost of site construction and the limitation of available channels at each cellular site. There are other ways to increase q, as mentioned in Chap. 6. An adequate system design will help to reduce the cochannel cross talk.

The channel combiner. The signal isolation among the forward voice channels in a channel combiner is 17 dB.[4] The loss resulting from inserting the signal into the combiner is about 3 dB. The requirement of IM product suppression is about 55 dB. If one outlet is not matched well, the signal isolation is less than 17 dB. Therefore, for each channel an isolator is installed to provide an additional 30-dB of isolation with a 0.5-dB insertion loss. This isolator prevents any signal from leaking back to the power amplifier (see Sec. 7.7.1). Spurious signals can be cross-coupled to this weak channel while transmitting. This kind of cross-coupled interference can be eliminated by routinely checking impedance matching at the combiner.

Telephone-line cross talk. Sometimes cross talk can result from cable imbalance or switching error at the central office and be conveyed to the customer through the telephone line. Minimizing this type of cross talk should be given the same priority as reducing the number of call drops, discussed earlier (Chap. 4 and Sec. 6.2).

7.6 Effects on Coverage and Interference by Applying Power Decrease, Antenna Height Decrease, Beam Tilting

Communications engineers sometimes encounter situations where coverage must be reduced to compensate for interference. There are several ways of doing this. Reorienting the directional-antenna patterns, changing the antenna beamwidth, or synthesizing the antenna pattern were discussed in Chap. 6. There are two additional methods, decreasing the power and decreasing the antenna height. Both methods are effective, and engineers often have difficulty choosing between them. Which one is better? The answer is dependent on the situation.

7.6.1 Choosing a proper cell site

Given a fixed transmitted power and a cell-site antenna height, the coverage contours of a cell site for different signal reception levels can be obtained from either the measurement or from the prediction model described in Chap. 4. A typical contour is shown in Fig. 7.11. Because of the irregular terrain contours, contours between different reception levels are not equally spaced.

When a cell site is selected, we must determine whether an ultra-high-frequency (UHF) TV station is nearby (see Sec. 7.9) and whether any future nearby ongoing construction would affect signal coverage from the cell site later. We must check the local noise level and be sure that no spurious signals fall in the cellular frequency band.

Finally, if we are using an existing multiantenna tower, we must ensure that the grounding and shielding are adequate. Otherwise the interference level could become very high and weaken cell-site operation. Sometimes a special isolator may be provided if an AM broadcasting antenna is colocated on the same tower.

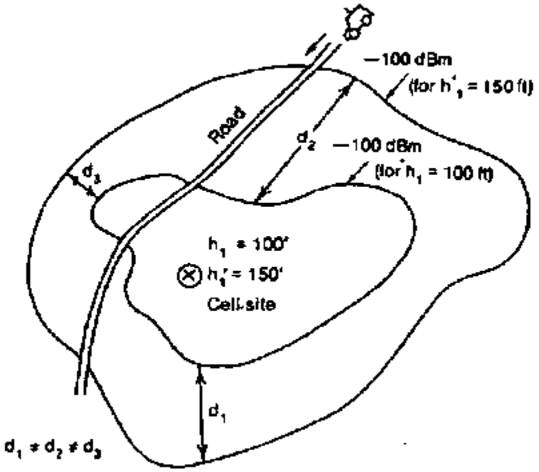


Figure 7.11 Signal-strength contour shape changing as the antenna height changes.

7.6.2 Power decrease

As long as the setup of the antenna configuration at the cell site remains the same, and if the cell-site transmitted power is decreased by 3 dB, then the reception at the mobile unit is also decreased by 3 dB. This is a one-on-one (i.e., linear) correspondence and thus is easy to control.

7.6.3 Antenna height decrease

When antenna height is decreased, the reception power is also decreased. However, the formula [see Eq. (4.10-2)]

$$\text{Antenna height gain (or loss)} = 20 \log \frac{h'_{e1}}{h_{e1}}$$

is based on the difference between the old and new effective antenna heights and not on the actual antenna heights. Therefore, the effective antenna height is the same as the actual antenna height only when the mobile unit is traveling on flat ground. It is easy to decrease antenna height to control coverage in a flat-terrain area. For decreasing antenna height in a hilly area, the signal-strength contour shown in Fig. 7.12*a* is different from the situation of power decrease shown in Fig. 7.12*b*. Therefore a decrease in antenna height would affect the coverage; thus antenna height becomes very difficult to control in an

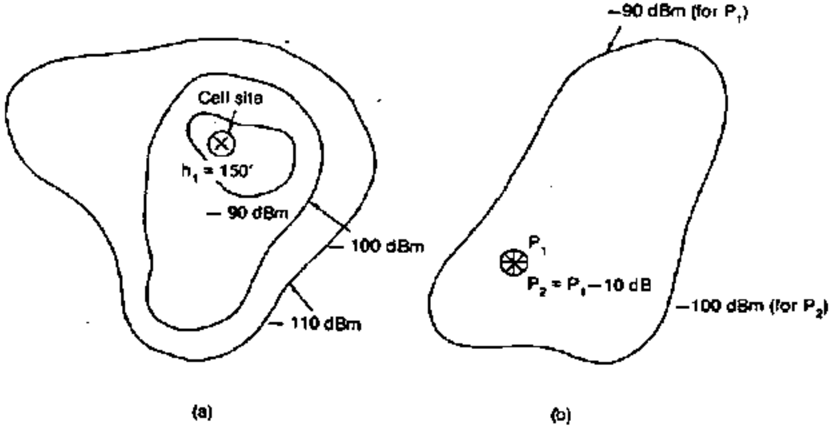


Figure 7.12 The signal-strength effect as measured by different parameters. (*a*) Different signal-strength contours. (*b*) Signal-strength changes with power changes.

overall plan. Some area within the cell may have a high attenuation while another may not.

7.6.4 Antenna patterns

The design of different antenna patterns is discussed and illustrated in Chap. 5. Here we would like to emphasize that the design of the antenna pattern should be based on the terrain contour, the population and building density, and other conditions within a given area. Of course, this is often difficult to do. For instance, implementation of antenna tilting or use of an umbrella pattern might be necessary in certain areas in order to reduce interference.

Sidelobe control (i.e., control of secondary lobe formation in an antenna radiation pattern) is also very critical in the implementation of a directional antenna. Coverage can be controlled by means of the following methods.

Using multiple antennas. In a multiple directional antenna pattern, the antennas can have different power outputs and each antenna can form a desired pattern. Two configurations can be mentioned.

1. All the antennas are facing outward (see Fig. 7.13*a*). The resultant pattern is always difficult to control because ripples and deep nulls frequently form.

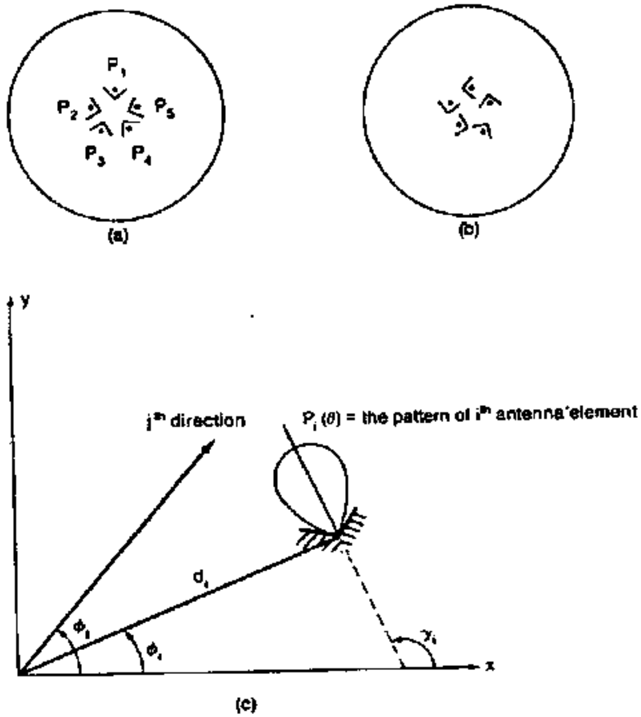


Figure 7.13 Engineering a desired pattern with directional antennas. (*a*) Five directional antennas facing outward; (*b*) a skewed configuration of five directional antennas; (c) the coordinate.

2. With skewed directional antennas[6] (see Fig. 7.13*b*), the resultant pattern becomes smoother. Therefore, this configuration is more attractive.

Using a synthesis of power pattern. The use of steepest descent techniques for searching the antenna parameters by giving an actual pattern and a desired pattern is introduced here. The signal strength contour obtained from Chap. 4 will be used. The difference between the two patterns, actual and desired, or error ϵ, can be expressed as

$$\epsilon(\phi, d, I, \alpha, \gamma) = \sum_{j=1}^{M} W_j(P_j - Q_j)^2 \tag{7.6-1}$$

The parameters ϕ, d, and γ are shown in Fig. 7.13*c*, where I_i and α_i are the amplitude and phase of *i*th element, respectively. P_j is the desired field strength at the jth direction, and Q_j is the given (measured) field strength at the jth direction. All cells may be divided into M small angles, and the jth direction is one of these angles. In Eq. (7.6-1), W_j is a weighting function. When a nonuniform pattern is to be synthesized $W_j \neq 1$. The steepest descent technique can be applied to find the five parameters associated with pattern P_j which will yield the minimum ϵ in Eq. (7.6-1).

If we are using L elements, then P_j in Eq. (7.6-1) is the desired radiation field strength.

$$P_j = \sum_{i=1}^{L} P_i(\phi_j - \gamma_i)I_i \times \exp\left\{-j\left[\frac{2\pi d_i}{\lambda}\cos(\phi_j - \phi_i) - \alpha_i\right]\right\} \qquad (7.6\text{-}2)$$

where $P_i(\phi)$ is the individual pattern of ith element. The magnitude and phase of the ith-element excitation are I_i and α_i, respectively. The remaining variables of Eq. (7.6-2) as shown in Fig. 7.13c. Since ϵ is a function of five parameters are indicated in Eq. (7.6-1), we start with an initial guess for the parameters (ϕ_0, d_0, I_0, α_0, γ_0), and then apply the iterative equation

$$\beta_{n+1} = \beta_n - k_{\beta_i}\nabla_{\beta_i}\epsilon_n \qquad (7.6\text{-}3)$$

where β = one of five parameters

$\nabla_{\beta_i}\epsilon_n$ = component of $\nabla\epsilon$ corresponding to the variable β evaluated at a given point, say, $\beta_n = \phi_n(\beta_n, d_n, I_n, \alpha_n, \gamma_n)$

k_{β_i} = gain constant for the parameter β_i

The value k_{β_i} cannot be small; otherwise the convergent process would be very slow. The iterative process is repeated until $n = N$ is reached, that is, $\nabla_{\beta_i}\epsilon_N = 0$. Then from Eq. (7.6-3), $\beta_{n+1} = \beta_n = \beta_i$ for any one of five parameters for the ith antenna element.

The same procedures apply for all elements, and all calculations can be performed by computer.

Caution: Because the terrain is not flat, the signal strengths in all directions are not uniformly attenuated at equal distances; thus, we must first obtain an antenna pattern (not desired) corresponding to a cell boundary in the actual field from a set of predetermined parameters (assume that the current distributions of all antenna elements are the same) and then convert the undesired pattern through the use of an iteration process to a desirable pattern that can be used in the field. The propagation model described in Chap. 4 will serve this purpose. Thus we can apply this iterative process to practical problems.

7.6.5 Transmitting and receiving antennas at the cell site

At the base station, the transmitted power of 100 W (+50 dBm) plus an antenna gain of 9 dBi is assumed at one transmitting antenna. The receiving antenna, located at the same site, also has a gain of 9 dBi and receives a mobile signal of −100 dBm. The difference in signal strength is

$$(50 + 9 + 9) \text{ dBm} - (-100 \text{ dBm}) = +168 \text{ dB}$$

If the space separation between a transmitting antenna and a receiving antenna is 15 m (50 ft) horizontally, the signal isolation obtained from the free-space formula is 56 dB.

The 45-MHz bandpass filter followed by the receiving antenna has at least a 55-dB rejection for signals arriving from the 870- to 890-MHz transmission band. However, the two numbers added together is 111 dB, which is still not sufficient (57 dB short). That is why the transmitting antenna and receiving antenna are not mounted in the same horizontal plane, but rather on the same vertical pole, if they are omnidirectional. This restriction can be moderated for directional antennas because of the directive patterns.

7.6.6 A 39-dBμ and a 32-dBμ boundary

The Federal Communications Commission (FCC) has used a specified received signal strength[9] for the coverage boundary, which is 39 dBμ (dB in μV/m). This value converts to a received power of −93 dBm for dipole or monopole matching on a 50-Ω load at 850 MHz (see Secs. 5.1.3 or 13.3.3). The value of 39 dBμ (i.e., −93 dBm) should be tested to determine if it is too high for use at the cell boundary in the cellular system.

We can calculate an acceptable level as follows. As we know, the accepted carrier-to-noise ratio for good quality (agreed on by most system operators) is 18 dB. The thermal noise level kTB with a bandwidth of 30 kHz and a temperature of 17°C is −129 dBm.

The receiver front-end noise N_f of an average-quality receiver is 9 dB. The noise figure NF usually would add the front-end noise N_f of the receiver and the noise N_{cm} introduced from the cellular mobile environment.

$$\text{NF} = \sqrt{N_f^2 + N_{cm}^2} \qquad \text{dB}$$

N_{cm} can either increase or decrease, depending on the system design. The earlier data indicate that N_{cm} can be neglected for 900-MHz curves.[7,8] If we now introduce a safety factor and let $N_{cm} = 6$ dB then

$$\mathrm{NF} = \sqrt{(9)^2 + (6)^2} = 11\ \mathrm{dB}$$

The total noise level is $N = kTB + \mathrm{NF} = -118$ dBm. Because the required C/N is 18 dB, the lowest acceptable signal level is −100 dBm (−32 dBμ), which is 7 dB lower than −93 dBm (39 dBμ). In reality, the cell boundary or the handoff is based on the voice quality, that is, $C/N = 18$ dB or a level of −100 dBm; therefore, the FCC cell boundary of 39 dBμ or −93 dBm is 7 dB higher than the level provided by the system. Thus a cell boundary of 32 dBμ or −100 dBm proved to be sufficient for cellular coverage.

The two main advantages of using a 32-dBμ level (see Fig. 7.14) are that (1) fewer cell sites would be needed to cover a growth area and (2) less interference would be effected at the boundaries. A 32-dB boundary for cells in either boundary of a metropolitan statistical area (MSA) or a rural service area (RSA) is a proper operation, as opposed to a 39-dBμ boundary which is an artificial value.

In September 1991, the FCC was modifying rules pertaining to measurement of coverage. The idea was based on the reason which the author mentioned in the previous edition of this book. The FCC proposes the following formula to define a cellular geographic service area (CGSA):

$$d = 1.05 \times H^{0.34} \times P^{0.17} \qquad \text{(FCC)} \qquad (7.6\text{-}4)$$

where d is the distance from the cell site antenna to the reliable service area boundary in miles, H is the antenna height above average terrain in feet, and P is the effective radiated power (ERP) in watts. This formula approximates this distance to the 32-dBμ contour predicted by Carey.

The prediction based on the Lee model also can be derived from Eq. (4.2-18) as follows

$$d = 0.348 \times H^{0.52} \times P^{0.26} \qquad \text{(Lee)} \qquad (7.6\text{-}5)$$

7.7 Effects of Cell-Site Components

7.7.1 Channel combiner

A fixed-tuned channel combiner at the transmitting side. A channel combiner is installed at each cell site. Then all the transmitted channels can be combined with minimum insertion loss and maximum signal isolation between channels. Of course, we can eliminate the channel combiner by letting each channel feed to its own antenna. Then a 16-

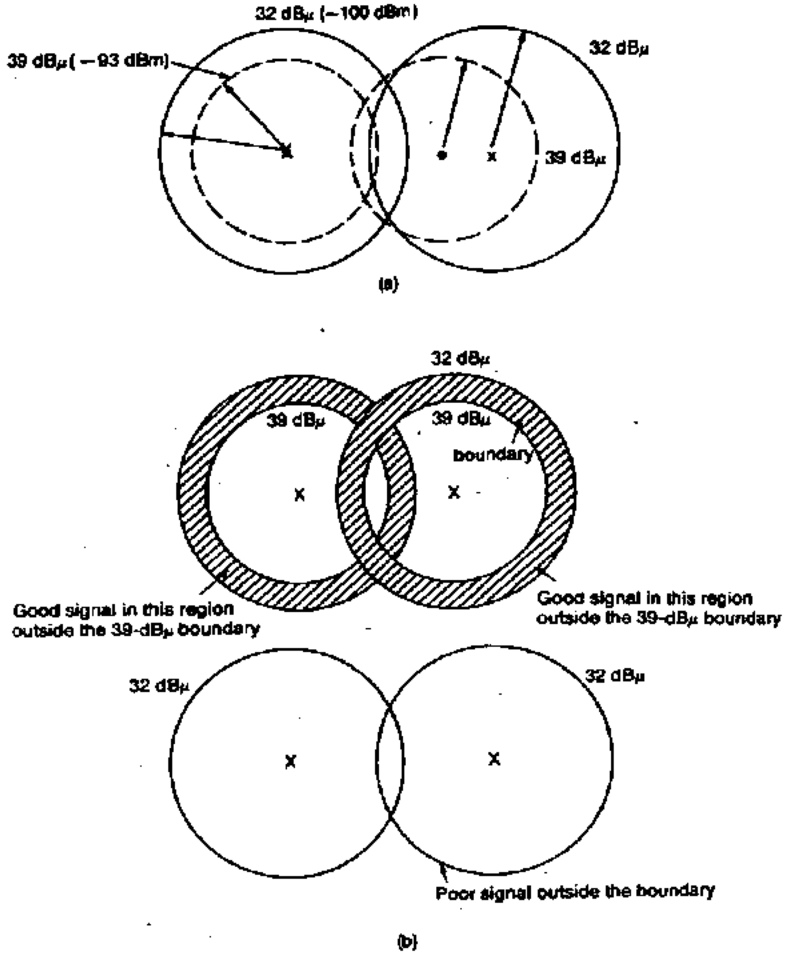


Figure 7.14 (*a*) Using a 32-dB boundary needs fewer cells to cover the area. (*b*) A signal outside its boundary generates noise.

channel site will have 16 antennas for operation. It is an economical and a physical constraint.

A conventional combiner has a 16-channel combined capacity based on the frequency subset of 16 channels, and it causes each channel to lose 3 dB from inserting the signal through the combiner. The signal isolation is 17 dB because each channel is 630 kHz or 21 channels apart from neighboring channels (Fig. 7.15*a*). The intermodulation at the multiplexer is controlled by ferrite isolators, which provide a 30-

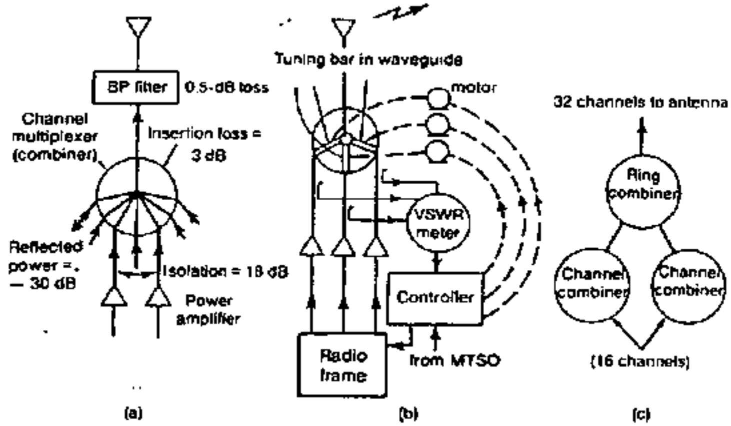


Figure 7.15 Different kinds of channel combiners. (*a*) Fixed-tuned combiner, (*b*) tunable combiner, (*c*) ring combiner.

dB reverse loss. The intermodulation (IM) products are at least 55 dB down from the desired signals. Therefore, the IM will not affect channels within the transmitted band design from this.

Each cable fed into a combiner must be properly shielded. Because it is a nonlinear device, undesired signal leakage into another channel would occur before the combiner can produce the IM products, which would in turn, produce cross-coupled interference. Therefore, proper shielding and impedance match are very important. Fixed-tuned combiners are tuned to match the impedances of a set of fixed frequencies which are assigned to a combiner.

A frequency-agile combiner.[11] This combiner is capable of returning to any frequency by remote control in real time. The remote control device is a microprocessor. The combiner is a waveguide-resonator combiner with a tuning bar in each input waveguide as shown in Fig. 7.15*b*. The bar is mechanically rotated by a motor, and the voltage standing-wave ratio (VSWR) can be measured when the motor starts to turn. The controller receives an optimum reading after a full turn and is stopped at that position by the controller. The controller also has a self-adjusting potential. This combiner can be used when a dynamic frequency assignment is applied. In many cases, it is preferable to redistribute the frequency channels to avoid prominent interference in certain areas. To use this kind of combiner, cell-site transceivers should also be able to change their operating frequencies, which are controlled by the MTSO, accordingly. This kind of combiner can also be designed to be tuned electronically.

A ring combiner.[12] A ring combiner is used to combine two groups of channels into a single output. The insertion loss is 3 dB, and the signal isolation between channels is 35 to 40 dB. The function of a ring combiner is to combine two 16-channel combiners into one 32-channel output. Therefore, all 32 channels can be used by a single transmitting antenna. If a cell site has two antennas, up to 64 radio channels can be installed in it.

If all the channel-transmitted powers are low, it is possible to combine more than 32 channels by using two or three ring combiners before feeding them into one transmitting antenna. The total allowed transmitted power is a limiting factor. Some ring combiners have a 600-W power limitation. The use of ring combiners reduces adjacent channel separation. If two 16-channel regular combiners are combined with a ring combiner, the adjacent-channel separation at the ring combiner output can be 315 kHz, even though the adjacent-channel separation of each regular combiner is 630 kHz. It is simply a frequency offset of 315 kHz between two regular combiners.

7.7.2 Demultiplexer at the receiving end

A demultiplexer is used to receive 16 channels from one antenna. The demultiplexer is a filter bank as shown in Fig. 7.16. Then each receiving antenna output passes through a 25-dB-gain amplifier to a demultiplexer. The demultiplexer output has a 12-dB loss from the split of 16 channels.

$$\text{Split loss} = 10 \log 16 = 12 \text{ dB}$$

and the IM product at the output of the demultiplexer should be 65 dB down.[4] The two space-diversity antennas each connect to an umbrella filter (block A or B band filter) and have a 55-dB rejection from the other system band. If the undesired mobile unit is close to the cell site, then the preamplifier becomes saturated and generates IM at the output of the amplifier; these IM products (frequencies) could be felt in one of the weak incoming signals. This situation can lead to cross talk (see Sec. 7.4) which can be heard from both ends of the link because of a unique characteristic of cellular channels (see Sec. 7.5).

7.7.3 SAT tone

General description. The major function of a supervisory audio tone (SAT) is to ensure that a SAT tone is sent out at the cell site, is received by the mobile unit on a forward voice channel, is converted on a corresponding reverse voice channel, and is then sent back to the

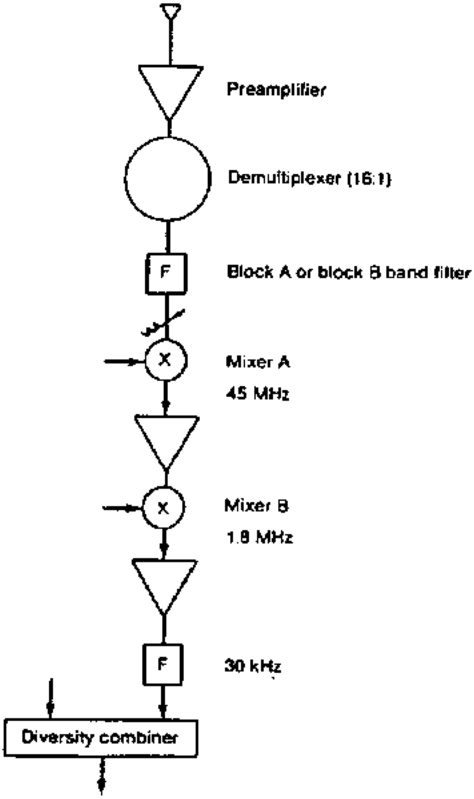


Figure 7.16 A typical cell-site channel receiver.

cell site within 5 s. If the time out is more than 5 s, the cell site will terminate the call.

Every cell site has been assigned to one of three SAT tones. The assignment of three SAT tones in a system is shown in Fig. 7.17. The cells have the same SAT tones, and the same channels are separated by $\sqrt{3}D$, which is farther than the cochannel distance D. Therefore, a receiver located at either the cell site or at the mobile unit and receiving the same frequency with different SAT tones will terminate the call.

Characteristics of SAT. There are three SAT tones, 5970 H, 6000 H, and 6030 Hz, spaced 30 Hz apart. They are narrowband frequency-modulated (FM) with a deviation of $f_\Delta = 2$ kHz. The modulation index is $\beta = \frac{1}{3}$. Let the SAT tone signal be

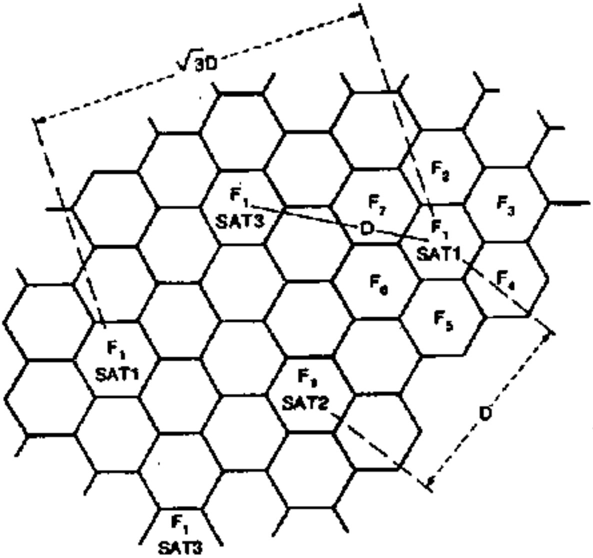


Figure 7.17 SAT spatial allocation.

$$x(t) = A_m \cos \omega_m t \tag{7.7-1}$$

and the modulated carrier is

$$x_c(t) = A_c \cos(\omega_c t + \beta \sin \omega_m t) \tag{7.7-2}$$

where $\beta = (A_m f_\Delta / f_m)$. Let the amplitude modulation $A_m = 1$; thus, since β is small, Eq. (7.7-2) becomes

$$x_c(t) \approx A_c \cos(\omega_c t) + \frac{A_c\beta}{2} \times \cos[2\pi(f_c + f_m)t] - \frac{A_c\beta}{2} \cos[2\pi(f_c - f_m)t]$$

$$= R(t) \cos[\omega_c t + \phi(t)] \tag{7.7-3}$$

where[13]

$$R(t) = \sqrt{A_c^2 + \left(2\,\frac{\beta}{2}\,A_c \sin \omega_m t\right)^2}$$

$$\approx A_c\left[1 + \frac{\beta^2}{4} - \frac{\beta^2}{4} \cos 2\omega_m t\right] \tag{7.7-4}$$

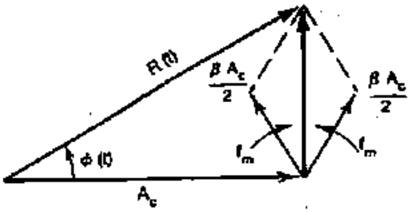


Figure 7.18 Narrowband FM for SAT.

$$\phi(t) = \arctan\left[\frac{2(\beta/2)A_c \sin \omega_m t}{A_c}\right] = \beta \sin \omega_m t \qquad (7.7\text{-}5)$$

The FM phasor diagram for $\beta << 1$ is shown in Fig. 7.18. Equation (7.7-4) represents an FM condition in which the amplitude of the carrier always remains constant. This means that the amplitude has no information content. This is a very common consideration in the mobile radio environment because of the severe fading which distorts the constant amplitude.

The SAT generator cannot deviate by more than ± 15 Hz while receiving the signal. The SAT detector uses this criterion to continuously accept or reject a returned SAT. It has been observed that two SATS with two different audio tone amplitudes can arrive at one cell. If the desired SAT tone is weaker than the undesired one by a certain ratio, then the SAT tone will deviate by ± 15 Hz. These conditions are discussed in Sec. 13.1.2. The filter bandwidth of the SAT tone detector relates to call-drop timing, which should be based on the unacceptable voice quality level. In theory, this level is different in different environment. Usually the smaller the filter bandwidth, the lower the call-drop rates. But the voice quality may be very poor before dropping the calls.

7.8 Interference between Systems

7.8.1 In one city

Let us assume that there are two systems operating in one city or one MSA. If a mobile unit of system A is closer to a cell site of system B while a call is being initiated through system A, adjacent channel interference or IM can be produced if the transmitted frequency of mobile unit A is close to the covered band of the received preamplifier at cell site B (see Fig. 7.19a). These IM products will then leak into the receiving channel of system B and cross talk will occur. This cross talk

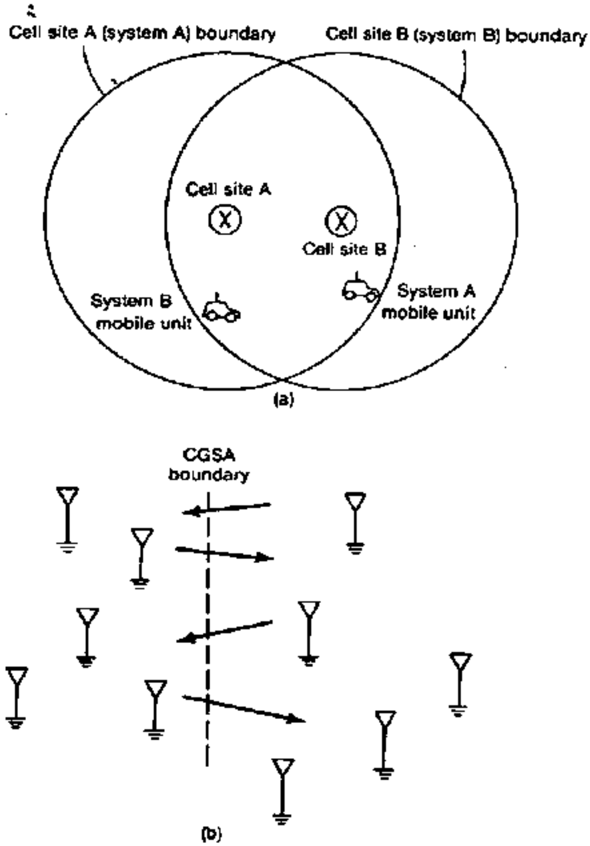


Figure 7.19 Intersystem interference. (*a*) System A cell sites in system B cell coverage; (*b*) interference between two cellular geographic service area (CGSA) systems.

can be heard not only at the land-line side but also at the mobile unit because of the unique characteristics described in Sec. 7.5.

This cross-talk situation can be reduced by any of the following measures.

1. All cell sites in the two systems can be located together (*colocated*).
2. Adjacent channels (four or five channels) at each interface (see Fig. 7.6) of the new allocated voice channels between two of the systems should not be used.
3. To prevent a strong mobile signal from saturating the preamplifier at the cell site, a foreign-system signal should be −55 dBm down

from the cell-site reception point. Otherwise IM products can be produced and mixed with the desired system by passage through the system (band) block filter (see Fig. 7.16).

For instance, IM may occur in either of the following cases.

(2 × 838 − 832) MHz = 844 MHz (system B at the cell site)

Either signal (838 or 832 MHz) is strong; the IM will leak into the 844-MHz channel.

(2 × 834 − 836 MHz = 832 MHz (system A at the cell site)

Either signal (834 or 836 MHz) is strong; the IM will leak into the 832-MHz channel.

7.8.2 In adjacent cities

Two systems operating at the same frequency band and in two adjacent cities or areas may interfere with each other if they do not coordinate their frequency channel use. Most cases of interference are due to cell sites at high altitudes (see Fig. 7.19*b*). In any start-up system, a high-altitude cell site is always attractive to the designer. Such a system can cover a larger area, and, in turn, fewer cell sites are needed. However, if the neighboring city also uses the same system block, then the result is strong interference, which can be avoided by the following methods.

1. The operating frequencies should be coordinated between two cities. The frequencies used in one city should not be used in the adjacent city. This arrangement is useful only for two low-capacity systems.
2. If both systems are high capacity, then decreasing the antenna heights will result in reduction of the interference not only within each system but also between the two systems.
3. Directional antennas may be used. For example, if one system is high capacity and the other is low capacity, the low-capacity system can use directional antennas but still retain the high tower. In this situation frequency coordination between the two systems has to be worked out at the common boundary because all the allocated frequencies must be used by the high-capacity system in its service area but only some frequencies are used by the low-capacity system.

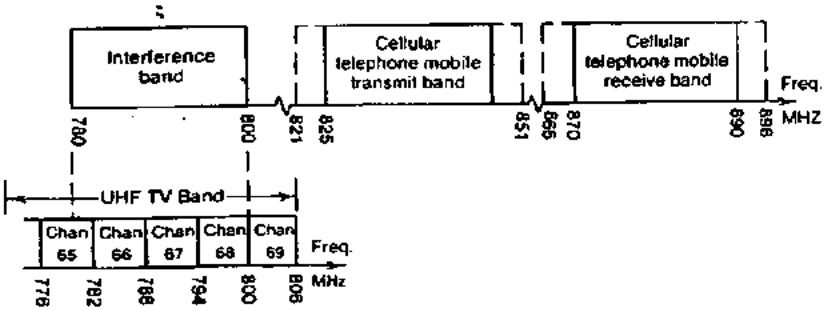


Figure 7.20 Cellular telephone frequency plan.

7.9 UHF TV Interference

Two types of interference can occur between UHF television and 850-MHz cellular mobile phones.

7.9.1 Interference to UHF TV receivers from cellular mobile transmitters

Because of the wide frequency separation between cellular phone systems and the media broadcast services (TV and radio) and the significantly high power levels used by the UHF TV broadcast transmitters, the likelihood of interference from cellular phone transmissions affecting broadcasting is very small.[14,15] There is a slight probability that when the cell-site transmission is 90 MHz above that of a TV channel, it can interfere with the image-response frequency of typical home TV receivers. Interference between TV and cellular mobile channels is illustrated in Fig. 7.20.

Some UHF TV channels overlap cellular mobile channels. These two types of service can interfere with each other only under the following conditions.

1. *Band region with overlapping frequencies.* Two services have been authorized to operate within the same frequency band region.
2. *Image interference region.* This is explained as follows. The TV receiver or the cellular receiver (mobile unit or cell site) can receive two transmitted signals, for instance, one from a TV channel and one from a cellular system, and produce a third-order intermodulation product which falls within the TV or the mobile receive band.

Let

f_{Tm} = mobile transmit frequency

= f_{Rc} = cell-site receive frequency = $f_{Tc} - 45$ MHz

f_{Rm} = mobile receive frequency

= $f_{Tm} + 45$ MHz = f_{Tc} = cell-site transmit frequency

$f_{T,\mathrm{TV}}$ = TV transmit frequency

$f_{R,\mathrm{TV}}$ = TV receive frequency

Third-order intermodulation gives the following results in two cases of interfering UHF TV receivers.

Case 1. Let

$$2f_{Tm} - f_{T,\mathrm{TV}} = f_{Rm} \tag{7.9-1}$$

$$f_{Tm} = f_{Rm} - 45 \tag{7.9-2}$$

then

$$f_{Tm} = f_{T,\mathrm{TV}} + 45 \tag{7.9-3}$$

Since the mobile transmit frequency f_{Tm} lies in the 825- to 845-MHz band, and the TV transmit frequency $f_{T,\mathrm{TV}}$ lies in the 780- to 800-MHz band, f_{Tm} will interfere with the TV receiver as seen from Eq. (7.9-3). This interference region is called the *image interference region.*

Case 2. Let

$$2f_{Rc} - f_{T,\mathrm{TV}} = f_{Tc} \tag{7.9-4}$$

then

$$f_{Rc} = f_{Tc} - 45 \tag{7.9-5}$$

and

$$f_{Tc} = f_{T,\mathrm{TV}} + 90 \tag{7.9-6}$$

Because the cell-site transmit frequency f_{Tc} lies in the 870- to 890-MHz band, and $f_{T,\mathrm{TV}}$ lies in the 780- to 800-MHz band, f_{Tc} will interfere with the TV receiver, as shown in Eq. (7.9-6). This interference region is called the image interference region.

In these two cases an image-interference rejection range of 40 to 50 dB isolation across the UHF TV band is required to prevent this interference. The results from the two cases are as follows.

Case 1: When the mobile transmitter is located near a TV receiver (Eq. 7.9-3). The minimum grade B television service contour of an accepted TV receiver level is −63 dBm with a receiver antenna gain of 6 dB referring to dipole gain. Roughly, this kind of TV station has a coverage of a 56-km (35-mi) radius. Since the cellular telephone mobile unit has an effective radiated power (ERP) of about 37 dBm, the path loss between the TV receiver and the mobile unit must exceed 100 dB (= 63 + 37). The TV antenna height at each residence normally is about $h_2 = 10$ m. The mobile antenna height is about $h_1 = 2$ m. Assume that the cross-modulation loss between two frequency bands is 80 dB and the polarization coupling loss between the bands is 10 dB. Using the formula derived in Eq. (4.2-19), we obtain

$$-63 = 37 - 156 - 40 \log \frac{d_1}{d_0} + 10 \log h_1 + 20 \log h_2 + 6 - (80 + 10) \text{ dB} \quad (7.9\text{-}7)$$

Substitution of $h_1 = 2$ m (6 ft) and $h_2 = 10$ m (30 ft) into Eq. (7.9-7) yields

$$140 = -40 \log d_1 + 7.78 + 29.54$$

We can solve d_1 as

$$d_1 = 10^{-2.57} = 0.00239 \text{ mi} = 14 \text{ ft}$$

We find that the required distance from a transmitting cellular mobile unit to a TV receiver is only 14 ft. Besides, a mobile unit is always moving while the TV receivers usually are off; thus, the chance of mobile unit interference occurring within 14 ft of the receiver while TV receivers are operative is very slim. In addition, the chances are that the mobile unit would remain in the area of interference for only 5 to 10 s.

Case 2: When the cell site transmitter is located near a TV receiver (Eq. 7.9-6). Usually cell-site antennas are located on high towers, and the vertical antenna pattern usually produces a null under the antenna tower. Therefore, even though Eq. (7.9-6) indicates the possibility of cell-site interference, the TV receivers near the cell site will not be in the area of the main antenna beam and, clearly, the horizontally polarized TV wave will not be distorted by the cellular vertically polarized waves when it reaches the TV receiving antenna on the roof of the house. Because of these differences between antenna beam pattern and wave polarization, no strong interference can be seen in this case. We find that the required distance could be less than 200 m (700 ft). We should also consider the following key points.

1. The polarization coupling loss from vertical (cellular) to horizontal (TV) waves can be 10 dB, according to Lee and Yeh's data.[16]
2. The percentage of active mobile units in that area is small.

3. In the UHF TV fringe area, cable TV (CATV) usually provides the service.
4. Only four TV channels (Channels 65 to 68) can experience interference. The chance of one TV set tuning to one of these four "interference channels" and the active mobile unit happening to be in that area at the same time is slim.
5. Even if transmission from the mobile unit does interfere with TV reception, the interference time is very short (<15 s). Therefore, no interference should be encountered.

7.9.2 Interference of cellular mobile receivers by UHF TV transmitters

This type of image interference can occur in the following four cases. Here the image-interference region will be the same as that described in Sec. 7.9.1 but in the reversed direction.

Case 1. Let

$$2f_{Tm} - f_{T,TV} = f_{Rm} \tag{7.9-8}$$

Then

$$2f_{Tm} = 2(f_{Rm} - 45) \tag{7.9-9}$$

and

$$F_{T,TV} = 2f_{Tm} - f_{Rm} = f_{Rm} - 90 \text{ MHz} \tag{7.9-10}$$

Because the mobile unit receiver frequency f_{Rm} lies in the 870- to 890-MHz band, $f_{T,TV}$, which lies in the 780- to 800-MHz band, will interfere with the mobile unit receiver, as shown in Eq. (7.9-10).

Case 2. Let

$$2f_{Rc} - f_{T,TV} = f_{Tc} \tag{7.9-11}$$

Then

$$f_{Rc} = f_{Tc} - 45 \tag{7.9-12}$$

and

$$f_{Rc} = 2f_{Rc} - f_{T,TV} - 45 = f_{T,TV} + 45 \tag{7.9-13}$$

Since the cell-site receiver frequency f_{Rc} lies in the 825- to 845-MHz band, $f_{T,TV}$, which lies in the 780- to 800-MHz band, will interfere with the cell-site receiver as shown in Eq. (7.9-13). There are two additional, but less important, cases.

Case 3. When a mobile receiver approaches a TV transmitter, it is easy to find that transmission from the TV station will not interfere with the reception at the mobile receiver by following the same analysis shown in Sec. 7.9.1, case 2.

Case 4. When the cell-site receiver is only 1 mi or less away from the TV station, interference may result. However when the cell site is very close to the TV station, the interference decreases as a result of the two vertical narrow beams pointing at different elevation levels. For this reason it is advisable to mount a cell-site antenna in the same vicinity as the TV station antenna if the problems of shielding and grounding can be controlled.

7.10 Long-Distance Interference

7.10.1 Overwater path

The phenomenon is mentioned in several reports.[17,18]

1. A 41-mi overwater path operating at 1.5 GHz in Massachusetts Bay[17]
   a. Low ducts (<50 ft thick); steady signal well above normal level is received
   b. High ducts (≥100 ft thick); a high signal level generally on the average is received but with deep fading
2. A 275-mi overwater path operating at 812 and 857 MHz between Charleston, South Carolina and Daytona Beach, Florida
   a. Charleston—antenna height 500 ft above average terrain antenna pattern, omnidirectional ERP 220 W; receiving sensitivity less than 0.5 μV = −113 dBm (1 μV = −107 dBm) with a 50-Ω terminal
   b. Daytona Beach—antenna height 920 ft above average terrain antenna pattern, omnidirectional ERP 440 W; receiving sensitivity 0.7 μV = −110 dBm

Federal Express engineers have discovered the following phenomenon through study of their system.[18] The mobile units in Charleston within 1 to 2 mi of shoreline are capable of clear communication with a repeater station in Daytona Beach. The same situation applies when the mobile unit is in Daytona Beach. These clear path communications occur regardless of weather, time of day, or season. This is a tropospherical propagation, and we should eliminate it in cellular systems to avoid interference among systems in North America. One way of doing this is by use of umbrella antenna patterns.

7.10.2 Overland path

Tropospheric scattering over a land path is not as persistent as that over water and can be varied from time to time. Usually tropospheric propagation is more pronounced in the morning. The distance can be about 200 mi. Federal Express engineers have observed this long-distance propagation throughout their nationwide system.

References

1. V. H. MacDonald, "The Cellular Concept," *Bell System Technical Journal,* Vol. 58, January 1979, pp. 15–42.
2. S. W. Halpern, "Techniques for Estimating Subjective Opinion in High-Capacity Mobile Radio," *Microwave Mobile Symposium,* Boulder, Colorado, 1976.
3. F. E. Terman and J. M. Pettit, *Electronic Measurements,* McGraw-Hill Book Co., 1952.
4. N. Ehrlich, R. E. Fisher, and T. K. Wingard, "Cell-Site Hardware," *Bell System Technical Journal,* Vol. 58, January 1979, pp. 153–199.
5. W. C. Y. Lee, "Elements of Cellular Mobile Radio Systems," *IEEE Transactions on Vehicular Technology,* Vol. VT-35, May 1986, pp. 48–56.
6. J. Pecini and M. H. Idselis, "Radiation Pattern Synthesis for Broadcast Antennas," *IEEE Transactions on Broadcasting,"* Vol. BC-18, September 1972, pp. 53–62.
7. *ITT Reference Data for Radio Engineers,* Howard W. Sams & Co., Indianapolis, 1968, pp. 2–27.
8. A. D. Spaulding and R. T. Disney, "Man-Made Radio Noise, Part I: Estimate for Business, Residential and Rural Areas," U.S. Department of Commerce, Office of Technical Services Report 74-38, June 1974.
9. E. N. Skomal, *Man-Made Radio Noise,* Van Nostrand Reinhold, 1978, Chap. 2.
10. FCC Application for Cellular Operation License Requirement.
11. Antenna Specialist Co., A Frequency-Agile Combiner.
12. Antenna Specialist Co., A Ring Combiner.
13. P. F. Panter, *Modulation, Noise, and Spectral Analysis,* McGraw Hill Book Co., 1965, p. 248.
14. S. N. Ahmed and P. C. Constantinon, "A Mobile Interference Model into UHF Television Receivers," *IEEE Transactions on Vehicular Technology,* vol. VT-32, May 1983, pp. 206–208.
15. R. E. Fisher, "UHF Television Interference Associated with Cellular Mobile Telephone Systems," *IEEE Transactions on Vehicular Technology,* Vol. VT-33, August 1984, pp. 244–249.
16. W. C. Y. Lee and Y. S. Yeh, "Polarization Diversity System for Mobile Radio," *IEEE Transactions on Communications,* Vol. COM-20, October 1972, pp. 912–923.
17. S. S. Attwood (Ed.), *Radio Wave Propagation Experiments,* Vol. 2, Columbia University Press, 1946, Part I, pp. 3–47 (Chaps. 1 and 2).
18. G. W. Moor and S. Walton, Federal Express Inc., private communication.

Chapter

8

Frequency Management and Channel Assignment

8.1 Frequency Management

The function of frequency management is to divide the total number of available channels into subsets which can be assigned to each cell either in a fixed fashion or dynamically (i.e., in response to any channel among the total available channels).

The terms "frequency management" and "channel assignment" often crate some confusion. *Frequency management* refers to designating set-up channels and voice channels (done by the FCC), numbering the channels (done by the FCC), and grouping the voice channels into subsets (done by each system according to its preference). *Channel assignment* refers to the allocation of specific channels to cell sites and mobile units. A fixed channel set consisting of one or more subsets (see Sec. 8.1.2) is assigned to a cell site on a long-term basis. During a call, a particular channel is assigned to a mobile unit on a short-term basis. For a short-term assignment, one channel assignment per call is handled by the mobile telephone switching office (MTSO). Ideally channel assignment should be based on causing the least interference in the system. However, most cellular systems cannot perform this way.

8.1.1 Numbering the channels

The total number of channels at present (January 1988) is 832. But most mobile units and systems are still operating on 666 channels. Therefore we describe the 666 channel numbering first. A channel consists of two frequency channel bandwidths, one in the low band

	1A	2A	3A	4A	5A	6A	7A	1B	2B	3B	4B	5B	6B	7B	1C	2C	3C	4C	5C	6C	7C	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	
	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	
	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	
	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	
	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	
	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	
	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	
	148	149	150	151	152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	167	168	
	169	170	171	172	173	174	175	176	177	178	179	180	181	182	183	184	185	186	187	188	189	
	190	191	192	193	194	195	196	197	198	199	200	201	202	203	204	205	206	207	208	209	210	
	211	212	213	214	215	216	217	218	219	220	221	222	223	224	225	226	227	228	229	230	231	
	232	233	234	235	236	237	238	239	240	241	242	243	244	245	246	247	248	249	250	251	252	
Block A system	253	254	255	256	257	258	259	260	261	262	263	264	265	266	267	268	269	270	271	272	273	
	274	275	276	277	278	279	280	281	282	283	284	285	286	287	288	289	290	291	292	293	294	
	295	296	297	298	299	300	301	302	303	304	305	306	307	308	309	310	311	312	—	—	—	
	313	314	315	316	317	318	319	320	321	322	323	324	325	326	327	328	329	330	331	332	333	Control channel sets
	334	335	336	337	338	339	340	341	342	343	344	345	346	347	348	349	350	351	352	353	354	
	355	356	357	358	359	360	361	362	363	364	365	366	367	368	369	370	371	372	373	374	375	
Block B system	376	377	378	379	380	381	382	383	384	385	386	387	388	389	390	391	392	393	394	395	396	
	397	398	399	400	401	402	403	404	405	406	407	408	409	410	411	412	413	414	415	416	417	
	418	419	420	421	422	423	424	425	426	427	428	429	430	431	432	433	434	435	436	437	438	
	439	440	441	442	443	444	445	446	447	448	449	450	451	452	453	454	455	456	457	458	459	
	460	461	462	463	464	465	466	467	468	469	470	471	472	473	474	475	476	477	478	479	480	
	481	482	483	484	485	486	487	488	489	490	491	492	493	494	495	496	497	498	499	500	501	
	502	503	504	505	506	507	508	509	510	511	512	513	514	515	516	517	518	519	520	521	522	
	523	524	525	526	527	528	529	530	531	532	533	534	535	536	537	538	539	540	541	542	543	
	544	545	546	547	548	549	550	551	552	553	554	555	556	557	558	559	560	561	562	563	564	
	565	566	567	568	569	570	571	572	573	574	575	576	577	578	579	580	581	582	583	584	585	
	586	587	588	589	590	591	592	593	594	595	596	597	598	599	600	601	602	603	604	605	606	
	607	608	609	610	611	612	613	614	615	616	617	618	619	620	621	622	623	624	625	626	627	
	628	629	630	631	632	633	634	635	636	637	638	639	640	641	642	643	644	645	646	647	648	
	649	650	651	652	653	654	655	656	657	658	659	660	661	662	663	664	665	666	—	—	—	

Figure 8.1 Frequency-management chart.

and one in the high band. Two frequencies in channel 1 are 825.030 MHz (mobile transmit) and 870.030 MHz (cell-site transmit). The two frequencies in channel 666 are 844.98 MHz (mobile transmit) and 889.98 MHz (cell-site transmit). The 666 channels are divided into two groups: block A system and block B system. Each market (i.e., each city) has two systems for a duopoly market policy (see Chap. 1). Each block has 333 channels, as shown in Fig. 8.1.

The 42 set-up channels are assigned as follows.

Channels 313–333	block A
Channels 334–354	block B

The voice channels are assigned as follows.

Channels	1–312 (312 voice channels)	block A
Channels	355–666 (312 voice channels)	block B

These 42 set-up channels are assigned in the middle of all the assigned channels to facilitate scanning of those channels by frequency synthesizers (see Fig. 8.1). In the new additional spectrum allocation of 10 MHz (see Fig. 8.2), an additional 166 channels are assigned. Since a 1 MHz is assigned below 825 MHz (or 870 MHz), in the future, additional channels will be numbered up to 849 MHz (or 894 MHz) and will then circle back. The last channel number is 1023 ($=2^{10}$). There are no channels between channels 799 and 991.

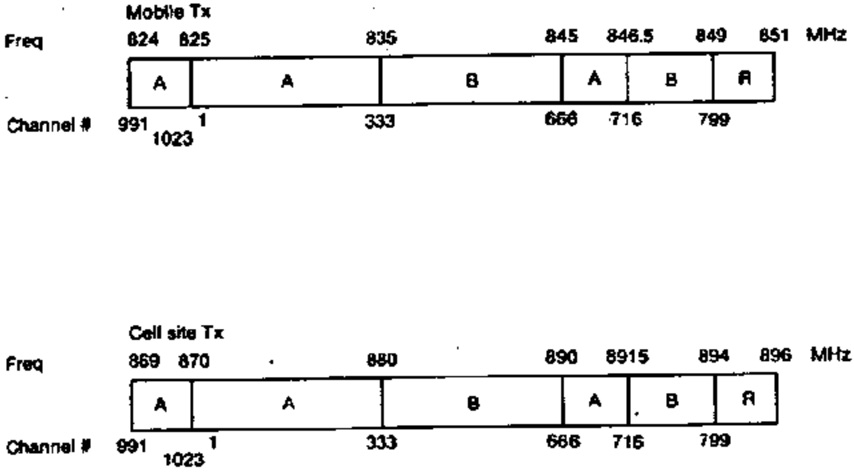


Figure 8.2 New additional spectrum allocation.

8.1.2 Grouping into subsets

The number of voice channels for each system* is 312. We can group these into any number of subsets. Since there are 21 set-up channels for each system, it is logical to group the 312 channels into 21 subsets. Each subset then consists of 16 channels. In each set, the closest adjacent channel is 21 channels away, as shown in Fig. 8.1. The 16 channels in each subset can be mounted on a frame and connected to a channel combiner. Wide separation between adjacent channels is required for meeting the requirement of minimum isolation. Each 16-channel subset is idealized for each 16-channel combiner. In a seven-cell frequency-reuse cell system each cell contains three subsets, $iA + iB + iC$, where i is an integer from 1 to 7. The total number of voice channels in a cell is about 45. The minimum separation between three subsets is 7 channels. If six subsets are equipped in an omnicell site, the minimum separation between two adjacent channels can be only three ($21/6 > 3$) physical channel bandwidths.

For example,

$$1A + 1B + 1C + 4A + 4B + 4C$$

$$\text{or} \quad 1A + 1B + 1C + 5A + 5B + 5C$$

The antenna arrangement for 90 voice channels was described in Sec.

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*Not including the new 83 voice channels.

5.4.1. The requirements for channel separation in a cell are discussed in this chapter.

8.2 Frequency-Spectrum Utilization

Since the radio-frequency spectrum is finite in mobile radio systems, the most significant challenge is to use the radio-frequency spectrum as efficiently as possible. Geographic location is an important factor in the application of the frequency-reuse concept in mobile cellular technology to increase spectrum efficiency. Frequency management involving the assignment of proper channels in different cells can increase spectrum efficiency. Thus, within a cell, the channel assignment for each call is studied. Other factors, such as narrowing of the frequency band, off-air call setup, queuing, and call redirect, are described in different chapters.

The techniques for increasing frequency spectrum can be classified as

1. Increasing the number of radio channels using narrow banding, spread spectrum, or time division (Chap. 13)
2. Improving spatial frequency-spectrum reuse (Chaps. 2, 6, and 7)
3. Frequency management and channel assignment (Chap. 8)
4. Improving spectrum efficiency in time (Chap. 14)
5. Reducing the load of invalid calls (Chap. 11)
   - *a*. Off-air call setup—reducing the load of set-up channels
   - *b*. Voice storage service for No-Answer calls
   - *c*. Call forwarding
   - *d*. Reducing the customers' Keep-Dialing cases
   - *e*. Call waiting for Busy-Call situations
   - *f*. Queuing

In this chapter we concentrate on frequency management and channel assignment (item 3).

8.3 Set-up Channels

Set-up channels, also called *control channels*, are the channels designated to set up calls. We should not be confused by the fact that a call always needs a set-up channel. A system can be operated without set-up channels. If we are choosing such a system, then all 333 channels in each cellular system (block A or block B) can be voice channels; however, each mobile unit must then scan 333 channels continuously and detect the signaling for its call. A customer who wants to initiate a call must scan all the channels and find an idle (unoccupied) one to use.

In a cellular system, we are implementing frequency-reuse concepts. In this case the set-up channels are acting as control channels. The 21 set-up channels are taken out from the total number of channels. The number 21 is derived from a seven-cell frequency-reuse pattern with three 120° sectors per cell, or a total of 21 sectors, which require 21 set-up channels. However, now only a few of the 21 set-up channels are being used in each system. Theoretically, when cell size decreases, the use of set-up channels should increase.

Set-up channels can be classified by usage into two types: *access channels* and *paging channels*. An access channel is used for the mobile-originating calls and paging channels for the land-originating calls. In a low-traffic system, access channels and paging channels are the same. For this reason, a set-up channel is sometimes called an "access channel" and sometimes called a "paging channel." Every two-way channel contains two 30-kHz bandwidths. Normally one set-up channel is also specified by two operations as a forward set-up channel (using the upper band) and a reverse set-up channel (using the lower band). In the most common types of cellular systems, one set-up channel is used for both paging and access. The forward set-up channel functions as the paging channel for responding to the mobile-originating calls. The reverse set-up channel functions as the access channel for the responder to the paging call. The forward set-up channel is transmitted at the cell site, and the reverse set-up channel is transmitted at the mobile unit. All set-up channels carry data information only.

8.3.1 Access channels

In mobile-originating calls, the mobile unit scans its 21 set-up channels and chooses the strongest one. Because each set-up channel is associated with one cell, the strongest set-up channel indicates which cell is to serve the mobile-originating calls. The mobile unit detects the system information transmitted from the cell site. Also, the mobile unit monitors the Busy/Idle status bits over the desired forward set-up channel. When the Idle bits are received, the mobile unit can use the corresponding reverse set-up channel to initiate a call.

Frequently only one system operates in a given city; for instance, block B system might be operating and the mobile unit could be set to "preferable A system." When the mobile unit first scans the 21 set-up channels in block A, two conditions can occur.

1. If no set-up channels of block A are operational, the mobile unit automatically switches to block B.

2. If a strong set-up signal strength is received but no message can be detected, then the scanner chooses the second strongest set-up channel. If the message still cannot be detected, the mobile unit switches to block B and scans to block B set-up channels.

The operational functions are described as follows.

1. *Power of a forward set-up channel [or forward control channel (FOCC)].* The power of the set-up channel can be varied in order to control the number of incoming calls served by the cell. The number of mobile-originating calls is limited by the number of voice channels in each cell site. When the traffic is heavy, most voice channels are occupied and the power of the set-up channel should be reduced in order to reduce the coverage of the cell for the incoming calls originating from the mobile unit. This will force the mobile units to originate calls from other cell sites, assuming that all cells are adequately overlapped.
2. *The set-up channel received level.* The set-up channel threshold level is determined in order to control the reception at the reverse control channel (RECC). If the received power level is greater than the given set-up threshold level, the call request will be taken.
3. *Change power at the mobile unit.* When the mobile unit monitors the strongest signal strength from all set-up channels and selects that channel to receive the messages, there are three types of message.
   a. *Mobile station control message.* This message is used for paging and consists of one, two, or four words—DCC, MIN, SCC, and VMAX (see Chap. 3).
   b. *System parameter overhead message.* This message contains two words, including DCC, SID, CMAX, or CPA (see Chap. 3).
   c. *Control-filler message.* This message may be sent with a system parameter overhead message, CMAC—a control mobile attenuation code (seven levels).
4. *Direct call retry.* When a cell site has no available voice channels, it can send a direct call-retry message through the set-up channel. The mobile unit will initiate the call from a neighboring cell which is on the list of neighboring cells in the direct call-retry message.

8.3.2 Paging channels

Each cell site has been allocated its own set-up channel (control channel). The assigned forward set-up channel (FOCC) of each cell site is used to page the mobile unit with the same mobile station control message (discussed in Chap. 3 and Sec. 8.3.1).

Because the same message is transmitted by the different set-up channels, no simulcast interference occurs in the system. The algorithm for paging a mobile unit can be performed in different ways. The simplest way is to page from all the cell sites. This can occupy a large amount of the traffic load. The other way is to page in an area corresponding to the mobile unit phone number. If there is no answer, the system tries to page in other areas. The drawback is that response time is sometimes too long.

When the mobile unit responds to the page on the reverse set-up channel, the cell site which receives the response checks the signal reception level and makes a decision regarding the voice channel assignment based on least interference in the selected sector or underlay-overlay region.

8.3.3 Self-location scheme at the mobile unit

In the cellular system, 80 percent of calls originate from the mobile unit but only 20 percent originate from the land line. Thus, it is necessary to keep the reverse set-up channels as open as possible. For this reason, the self-location scheme at the mobile unit is adapted. The mobile unit selects a set-up channel of one cell site and makes a mobile-originating call. It is called a *self-location scheme.*

However, the self-location scheme at the mobile unit prevents the mobile unit from sending the necessary information regarding its location to the cell site. Therefore, the MTSO does not know where the mobile is. When a land-line call is originated, the MTSO must page all the cell sites in order to search for the mobile unit. Fortunately, land-line calls constitute only 20 percent of land-line originating calls, so the cellular system has no problem in handling them. Besides, more than 50 percent of land-line originating calls are no response.

8.3.4 Autonomous registration

If a mobile station is equipped for autonomous registration, then the mobile station stores the value of the last registration number (REGID) received on a forward control channel. Also, a REGINCR (the increment in time between registrations) is received by the mobile station. The next registration ID should be (see Chap. 3)

$$\text{NXTREG} = \text{REGID} + \text{REGINCR}$$

This tells the mobile unit how long the registration should be repeatedly sent to the cell site, so that the MTSO can track the location of the mobile. This feature is not used in cellular systems at present. However, when the volume of land-line calls begins to increase or the number of cell sites increases, this feature would facilitate paging of the mobile units with less occupancy time on all set-up channels. The trade-off between the self-location scheme and autonomous registration is shown in the following two examples.

Example 8.1 The time spent in the set-up channels for two schemes are compared.

1. Evaluation of a self-location scheme on a land-originating call. Assume that a system has 100 cell sites and a call paging has to reach all 100 cell sites. If every page takes 100 ms and there are 2000 land-originating calls per hour during a busy hour, then the air time spent for the paging during the busy hour is

$$100 \times (100 \text{ ms}) \times 2000 = 20{,}000 \text{ s} = 333 \text{ min/h}$$

This is the time spent on all set-up channels.

2. Evaluation of a registration scheme used on an idle stage for locating mobile units. Assume that the registration for each mobile unit is five times per hour. Each registration takes 100 ms. If 20,000 mobile units are on the road, then

$$(5 \times 100 \text{ ms}) \times 20{,}000 = 1000 \text{ s} = 166.7 \text{ min/h}$$

This is the time spent on all set-up channels.

In Example 8.1, the time spent on the set-up channels for a self-location scheme is twice as much as that for a registration scheme. In this particular case, the registration scheme is preferable to the self-location scheme.

Example 8.2 Assume that the reverse set-up channels also take the mobile-originating calls, which make up 80 percent of the total number of calls. Assume that 2500 land-originating calls constitute 20 percent of the total number of calls; then the mobile-originating calls represent 10,000 calls per hour handled by the MTSO. Each call initiation takes about 300 ms. Then

$$10{,}000 \times 300 = 3000 \text{ s} = 50 \text{ min}$$

The 50 min is occupied in both schemes. This is because for a mobile-originating call the self-location scheme provides a negligible time for selecting a desired cell site on a reverse set-up channel. The same negligible time is provided by using the registration scheme for selecting the desired cell site.

In a busy (rush) hour, the attempted call originating at a mobile unit is searching for an idle bit sent from the cell site. If an idle bit cannot be received at the mobile unit after 10 attempts, then a busy tone is heard at the mobile unit.

Therefore, the 50 min calculated above assumes that all 10,000 calls are not blocked. In reality, there is always a certain amount of call blocking during a rush hour. Therefore, even though the MTSO will spend 50 min in a system to process 10,000 calls per hour, the actual attempt calls can be much higher.

8.3.5 Traffic load on a set-up channel and on *N* voice channels

When the traffic of a cell is increasing, more radios will be installed. When a cell has 90 voice channels (radios), one set-up channel must coordinate them in order to set up the calls. On the average, the cell site takes a mobile-originating call on a reverse set-up channel for 100 ms, and the interval between calls is 25 ms (including calls colliding in the air). Thus, in 1 h, if a queuing scheme is applied, the maximum number of calls that a set-up channel can accommodate is

$$\frac{3600 \times 1000}{125 \text{ ms}} = 28{,}800 \text{ calls/h}$$

This equation is based on the assumption that the incoming calls from the mobile units are waiting for the idle bits showing on the forward set-up channel before sending the requests. This is equivalent to a queuing scheme. In general, the waiting period is 1 to 2 s. If the set-up channel is busy during this period, the mobile unit will periodically continue to search for idle channels about every 100 ms. Then the initiating call will be blocked after 10 attempts. An estimate of call blocking can be obtained by using a queuing model. Without queuing schemes, the maximum numer of initiating calls that the set-up channel can take during a busy hour, assuming five attempts per call, is 5760 calls per hour.

To calculate the traffic load on 90 voice channels, let us assume a blocking probability of 0.02 and a holding time of 100 s. Now we can check the offered load a from Table 1.1.

$$a = 78.3$$

The number of calls is

$$M = \frac{78.3 \times 3600}{100} = 2818 \text{ calls/h}$$

The carried load of a set-up channel is always greater than the carried load of the 90 voice channels. A load of more than 90 radios in a cell is not unusual. However, the number of voice channels in a cell rarely exceeds 120. Therefore one set-up channel is used in a cell.

8.3.6 Separation between access and paging

All 21 set-up channels are actually paging channels. The access channel can be assigned by the MTSO as a channel other than the 21 set-up channels in a cell. The mobile unit receives the access channel information from the forward paging channels. In certain cases, as land-originating calls increase, one set-up channel cannot handle all set-up traffic in a cell. In such cases another channel in a group of voice channels is used as an access channel. Now the land-originating calls are using paging channels and the mobile-originating calls are using access channels.

8.3.7 Selecting a voice channel

Assume that a mobile unit calls or responds to a call through a reverse set-up channel which is received from an omnidirectional antenna and the voice channels are assigned from a forward set-up channel at one of three 120°-sector directional antennas.

For mobile-originating calls. The mobile unit selects a cell site based on its received signal-strength indicator (RSSI) reading. When a call of a mobile unit is received by the cell site, the set-up channel receives it through an omnidirectional antenna. The cell-site RSSI scans the incoming signals through three directional antennas and determines which sector is the strongest one. The MTSO then assigns a channel from among those channels designated in that sector. In some systems, a set-up channel is assigned to each sector of a cell.

For paging calls. When any call responds to the cell site, the cell-site RSSI will measure the incoming signal from the three directional antennas and find the strongest sector in which the channel can be assigned to the mobile unit.

8.4 Definition of Channel Assignment

8.4.1 Channel assignment to the cell sites—fixed channel assignment

In a fixed channel assignment, the channels are usually assigned to the cell site for relatively long periods. Two types of channels are assigned: set-up channels and voice channels.

Set-up channels. There are 21 set-up channels assigned each cell in a $K = 4$, $K = 7$, or $K = 12$ frequency-reuse pattern. If the set-up channel antennas are omnidirectional, then each cell only needs one set-up channel. This leaves many unused set-up channels. However, the set-up channels of blocks A and B are adjacent to each other. In order to avoid interference between two systems, the set-up channels in the neighborhood of Channel 333 (block A) and Channel 334 (block B) are preferably unused.

Voice channels. One way of dividing the total voice channels into 21 sets is exemplified in Sec. 8.1. The assignment of certain sets of voice channels in each cell site is based on causing minimum cochannel and adjacent-channel interference. Cochannel and adjacent channel interference can be calculated from equations in Chaps. 6 and 7.

Supervisory audio tone (SAT). This consists of three SATs. Based on the assignment of each SAT in each cell, we can show the method for further reducing cochannel interference, as mentioned in Sec. 7.7.2.

8.4.2 Channel assignment to traveling mobile units

This situation always ocurs in the morning, when cars travel into the city, and at night, when the traffic pattern reverses. If the traffic density is uniform, the unsymmetrical mobile-unit antenna pattern (assuming large backward energy from the motion of the vehicle) does not affect the system operation much. However, when the traffic becomes heavier as more cars approach the city, the traffic pattern becomes nonuniform and the sites closest to the city, or in the city, cannot receive the expected number of calls or handoffs in the morning because of the mobile unit antenna patterns. At night, as the cars move out of the city, the cell sites closest to the city would have a hard time handing off calls to the sites away from the city.

To solve these problems, we have to use less transmitted power for both set-up and voice channels for certain cell sites. We also have to raise the threshold level for reverse set-up channels and voice channels at certain cell sites in order to control the acceptance of incoming calls and handoff calls. Three methods can be used.

Underlay-overlay.[1] The traffic capacity at an omnidirectional cell or a directional cell (see Fig. 8.3) can be increased by using the underlay-overlay arrangement. The underlay is the inner circle, and the overlay is the outer ring. The transmitted powers of the voice channels at the site are adjusted for these two areas. Then different voice frequencies

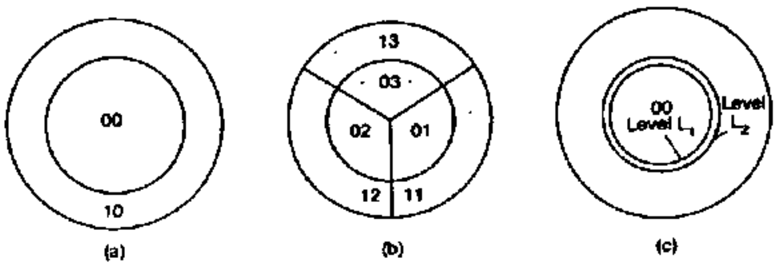


Figure 8.3 Underlaid-overlaid cell arrangements. (*a*) Undelay-overlay in omnicell; (*b*) underlay-overlay in sectorized cells; (*c*) two-level handoff scheme.

are assigned to each area. In an omnidirectional cell, the frequency-reuse distance of a seven-cell reuse pattern is $D = 4.6R$, where R is the radius of the cell. One overlay and one underlay are shown in Fig. 8.3*a*. Because of the sectorization in a directional cell, the channel assignment has a different algorithm in six regions (Fig. 8.3*b*), i.e., three overlay regions and three underlay regions. A detailed description is given in Sec. 8.5.4.

Frequency assignment. We assign the frequencies by a set of channels or any part of a set or more than one set of the total 21 sets. Borrowed-frequency sets are used when needed. On the basis of coverage prediction, we can assign frequencies intelligently at one site or at one sector without interfering with adjacent cochannel sectors or cochannel cells.

Tilted antenna. The tilted directional antenna arrangement can eliminate interference. Sometimes antenna tilting is more effective than decreasing antenna height, especially in areas of tall trees or at high sites. When the tilting angles become 22° or greater, the horizontal pattern creates a notch in the front of the antenna, which can further reduce the interference (see Fig. 6.10).

8.5 Fixed Channel Assignment

8.5.1 Adjacent-channel assignment

Adjacent-channel assignment includes neighboring-channel assignment and next-channel assignment. The near-end–far-end (ratio) interference, as mentioned in Sec. 7.3.1, can occur among the neighboring channels (four channels on each side of the desired channel). Therefore, within a cell we have to be sure to assign neighboring channels in an omnidirectional-cell system and in a directional-antenna-

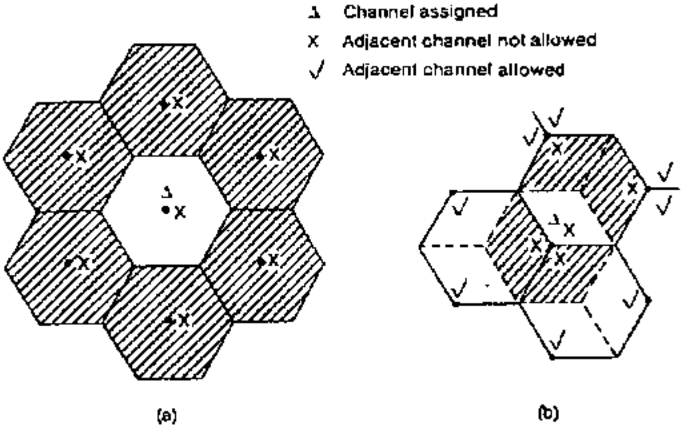


Figure 8.4 Adjacent channel assignment. (*a*) Omnidirectional-antenna cells; (*b*) directional-antenna cells.

cell system properly. In an omnidirectional-cell system, if one channel is assigned to the middle cell of seven cells, next channels cannot be assigned in the same cell. Also, no next channel (preferably including neighboring channels) should be assigned in the six neighboring sites in the same cell system area (Fig. 8.4*a*). In a directional-antenna-cell system, if one channel is assigned to a face, next channels cannot be assigned to the same face or to the other two faces in the same cell. Also, next channels cannot be assigned to the other two faces at the same cell site (Fig. 8.4*b*). Sometimes the next channels are assigned in the next sector of the same cell in order to increase capacity. Then performance can still be in the tolerance range if the design is proper.

8.5.2 Channel sharing and borrowing[2,3]

Channel sharing. Channel sharing is a short-term traffic-relief scheme. A scheme used for a seven-cell three-face system is shown in Fig. 8.5. There are 21 channel sets, with each set consisting of about 16 channels. Figure 8.5 shows the channel set numbers. When a cell needs more channels, the channels of another face at the same cell site can be shared to handle the short-term overload. To obey the adjacent-channel assignment algorithm, the sharing is always cyclic. Sharing always increases the trunking efficiency of channels. Since we cannot allow adjacent channels to share with the nominal channels in the same cell, channel sets 4 and 5 cannot both be shared with channel sets 12 and 18, as indicated by the grid mark. Many grid marks are indicated in Fig. 8.5 for the same reason. However, the

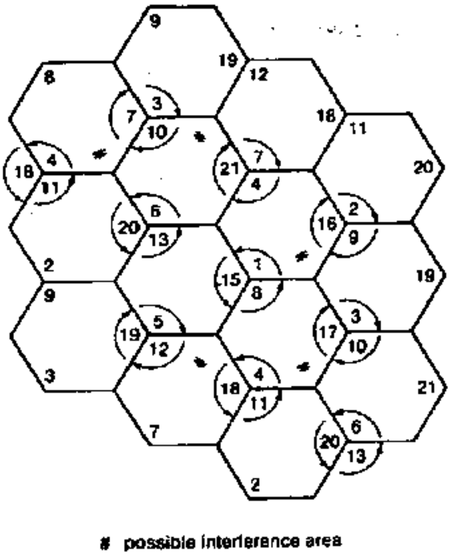


Figure 8.5 Channel-sharing algorithm.

upper subset of set 4 can be shared with the lower subset of set 5 with no interference.

In channel-sharing systems, the channel combiner should be flexible in order to combine up to 32 channels in one face in real time. An alternative method is to install a standby antenna.

Channel borrowing. Channel borrowing is usually handled on a long-term basis. The extent of borrowing more available channels from other cells depends on the traffic density in the area. Channel borrowing can be implemented from one cell-site face to another face at the same cell site.

In addition, the central cell site can borrow channels from neighboring cells. The channel-borrowing scheme is used primarily for slowly-growing systems. It is often helpful in delaying cell splitting in peak traffic areas. Since cell splitting is costly, it should be implemented only as a last resort.

8.5.3 Sectorization

The total number of available channels can be divided into sets (subgroups) depending on the sectorization of the cell configuration: the 120°-sector system, the 60°-sector system, and the 45°-sector system.

A seven-cell system usually uses three 120° sectors per cell, with the total number of channel sets being 21. In certain locations and special situations, the sector angle can be reduced (narrowed) in order to assign more channels in one sector without increasing neighboring-channel interference. This point is discussed in Sec. 10.6. Sectorization serves the same purpose as the channel-borrowing scheme in delaying cell splitting. In addition, channel coordination to avoid cochannel interference is much easier in sectorization than in cell splitting. Given the same number of channels, trunking efficiency decreases in sectorization.

Comparison of omnicells (nonsectorized cells) and sectorized cells

Omnicells. If a $K = 7$ frequency-reuse pattern is used, the frequency sets assigned in each cell can be followed by the frequency-management chart shown in Fig. 8.1. However, terrain is seldom flat; therefore, $K = 12$ is sometimes needed for reducing cochannel interference. For $K = 12$, the channel-reuse distance is $D = 6R$, or the cochannel reduction factor $q = 6$.

Sectorized cells. There are three basic types.

1. The 120°-sector cell is used for both transmitting and receiving sectorization. Each sector has an assigned a number of frequencies. Changing sectors during a call requires handoffs.
2. The 60°-sector cell is used for both transmitting and receiving sectorization. Changing sectors during a call requires handoffs. More handoffs are expected for a 60° sector than a 120° sector in areas close to cell sites (close-in areas).
3. The 120°- or 60°-sector cell is used for receiving sectorization only. In this case, the transmitting antenna is omnidirectional. The number of channels in this cell is not subdivided for each sector. Therefore, no handoffs are required when changing sectors. This receiving-sectorization-only configuration does not decrease interference or increase the D/R ratio; it only allows for a more accurate decision regarding handing off the calls to neighboring cells.

8.5.4 Underlay-overlay arrangement[1]

In actual cellular systems cell grids are seldom uniform because of varying traffic conditions in different areas and cell-site locations.

Overlaid cells. To permit the two groups to reuse the channels in two different cell-reuse patterns of the same size, an "underlaid" small cell is sometimes established at the same cell site as the large cell (see Fig. 8.3). The "doughnut" (large) and "hole" (small) cells are treated as two different cells. They are usually considered as "neighboring cells."

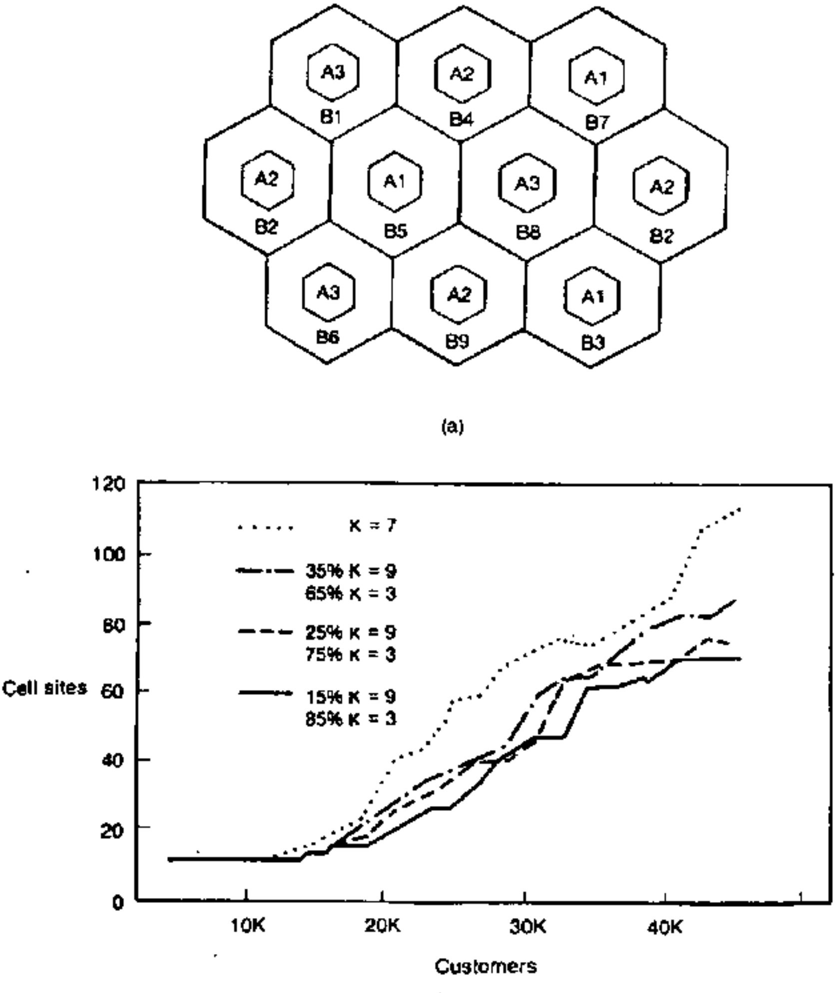
The use of either an omnidirectional antenna at one site to create two subring areas or three directional antennas to create six subareas is illustrated in Fig. 8.3*b*. As seen in Fig. 8.3, a set of frequencies used in an overlay area will differ from a set of frequencies used in an underlay area in order to avoid adjacent-channel and cochannel interference. The channels assigned to one combiner—say, 16 channels—can be used for overlay, and another combiner can be used for underlay.

Implementation. The antenna of a set-up channel is usually omnidirectional. When an incoming call is received by the set-up channel and its signal strength is higher than a level L, the underlaid cell is assigned; otherwise, the overlaid cell is assigned. The handoffs are implemented between the underlaid and overlaid cells. In order to avoid the unnecessary handoffs, we may choose two levels L_1 and L_2 and $L_1 > L_2$ as shown in Fig. 8.3*c*.

When a mobile signal is higher than a level L_1 the call is handed off to the underlaid cell. When a signal is lower than a level L_2 the call is handed off to the overlaid cell. The channels assigned in the underlaid cell have more protection against cochannel interference.

Reuse partition. Through implementation of the overlaid-cell concept, one possible operation is to apply a multiple-K system operation, where K is the number of frequency-reuse cells. The conventional system uses $K = 7$. But if one K is used for the underlaid cells, then this multiple-K system can have an additional 20 percent more spectrum efficiency than the single K system with an equivalent voice quality. In Fig. 8.6*a*, the $K = 9$ pattern is assigned to overlaid cells and the $K = 3$ pattern is assigned to underlaid cells. Based on this arrangement the number of cell sites can be reduced, while maintaining the same traffic capacity. The decrease in the number of cell sites which results from implementation of the multiple K systems is shown in Fig. 8.6*b*. The advantages of using this partition based on the range of K are

1. The K range is 3 to 9; the operational call quality can be adjusted and more reuse patterns are available if needed.



(a)

(b)

Figure 8.6 Reuse-partition scheme. (*After Whitehead, Ref. 1.*) (*a*) Reuse partition $K_A = 3$; $K_B = 9$. (*b*) Reuse-partitioning performance.

2. Each channel set of old $K = 9$ systems is the subset of new $K = 3$ systems. Therefore, the amount of radio retuning in each cell in this arrangement is minimal.
3. When cell splitting is implemented, all present channel assignments can be retained.

8.6 Nonfixed Channel Assignment Algorithms[4-9]

8.6.1 Description of different algorithms

Fixed channel algorithm. The fixed channel assignment (FCA) algorithm is the most common algorithm adopted in many cellular systems. In this algorithm, each cell assigns its own radio channels to the vehicles within its cell.

Dynamic channel assignment. In dynamic channel assignment (DCA), no fixed channels are assigned to each cell. Therefore, any channel in a composite of 312 radio channels can be assigned to the mobile unit. This means that a channel is assigned directly to a mobile unit. On the basis of overall system performance, DCA can also be used during a call.

Hybrid channel assignment. Hybrid channel assignment (HCA) is a combination of FCA and DCA. A portion of the total frequency channels will use FCA and the rest will use DCA.

Borrowing channel assignment. Borrowing channel assignment (BCA) uses FCA as a normal assignment condition. When all the fixed channels are occupied, then the cell borrows channels from the neighboring cells.

Forcible-borrowing channel assignment.[9] In forcible-borrowing channel assignment (FBCA), if a channel is in operation and the situation warrants it, channels must be borrowed from the neighboring cells and at the same time, another voice channel will be assigned to continue the call in the neighboring cell.

There are many different ways of implementing FBCA. In a general sense, FBCA can also be applied while accounting for the forcible borrowing of the channels within a fixed channel set to reduce the chance of cochannel assignment in a reuse cell pattern.

The FBCA algorithm is based on assigning a channel dynamically but obeying the rule of reuse distance. The distance between the two cells is *reuse distance,* which is the minimum distance at which no cochannel interference would occur.

Very infrequently, no channel can be borrowed in the neighboring cells. Even those channels currently in operation can be forcibly borrowed and will be replaced by a new channel in the neighboring cell

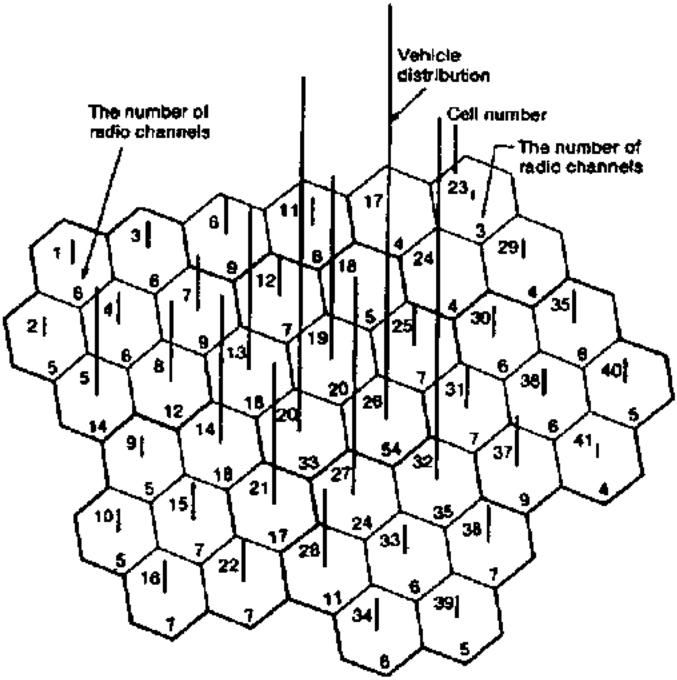


Figure 8.7 Cellular system. Vehicle and radio-channel distribution in the busy rush hour. *(After Sekiguchi et al., Ref. 9.)*

or the neighboring cell of the neighboring cell. If all the channels in the neighboring cells cannot be borrowed because of interference problems, the FBCA stops.

8.6.2 Simulation process and results

On the basis of the FBCA, FCA, and BCA algorithms, a seven-cell reuse pattern with an average blocking of 3 percent is assumed and the total traffic service in an area is 250 erlangs. The traffic distributions are (1) uniform traffic distribution—11 channels per cell; (2) a nonuniform traffic distribution—the number of channels in each cell is dependent on the vehicle distribution (Fig. 8.7). The simulation model is described as follows:

1. Randomly select the cell (among 41 cells).
2. Determine the state of the vehicle in the cell (idle, off-hook, on-hook, handoff).

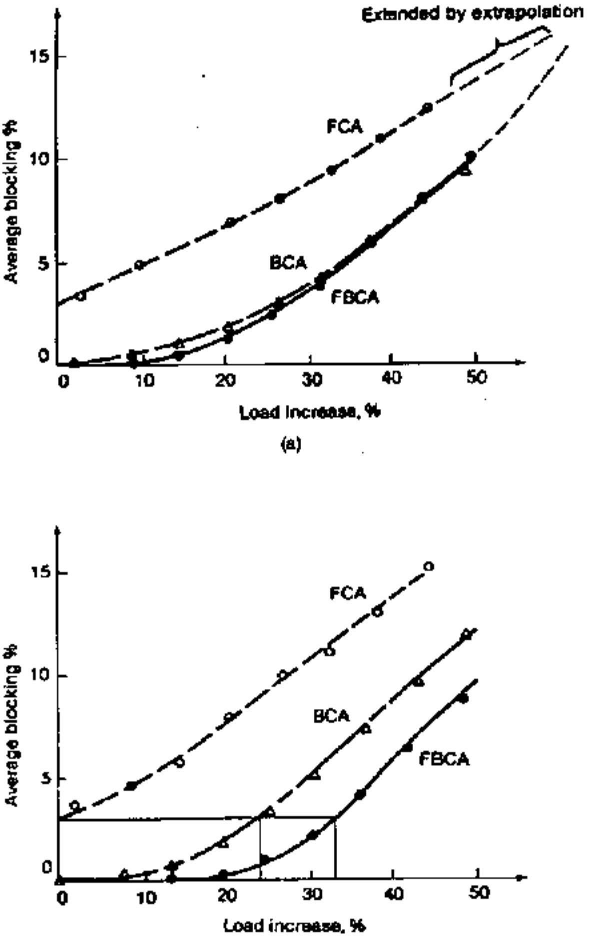


Figure 8.8 Comparison of average blockings from three different schemes. *(After Sekiguchi et al., Ref. 9)* (*a*) Average blocking in spatially uniform traffic distribution; (*b*) average blocking in spatially nonuniform traffic distribution.

3. In off-hook or handoff state, search for an idle channel. The average number of handoffs is assumed to be 0.2 times per call. However, FBCA will increase the number of handoffs.

Average blocking. Two average blocking cases illustrating this simulation are shown in Fig. 8.8. In a uniform traffic condition (Fig. 8.8*a*), the 3 percent blocking of both BCA and FBCA will result in a load increase of 28 percent, compared to 3 percent blocking of FCA. There is no difference between BCA and FBCA when a uniform traffic condition exists.

In a nonuniform traffic distribution (Fig. 8.8*b*), the load increase in BCA drops to 23 percent and that of FBCA increases to 33 percent, as at an average blocking of 3 percent. The load increase can be utilized in another way by reducing the number of channels. The percent increase in load is the same as the percent reduction in the number of channels.

Handoff blocking. Blocking calls from all handoff calls occurring in all cells is shown in Fig. 8.9. Handoff blocking is not considered as the regular cell blocking which can only occur at the call setup stage. In both BCA and FBCA, load is increased almost equally to 30 percent, as compared to FCA at 3 percent handoff blocking in uniform traffic (Fig. 8.9*a*). For a nonuniform traffic distribution, the load increase of both BCA and FBCA at 4 percent blocking is about 50 percent (Fig. 8.9*b*), which is a big improvement, considering the reduction in interference and blocking. Otherwise, there would be multiple effects from interference in several neighboring cells.

8.7 How to Operate with Additional Spectrum

On July 24, 1986 the FCC announced that a totally new additional spectrum of 10 MHz would be allocated to the cellular mobile industry. This spectrum provides 166 voice channels, with 83 channels for each carrier. The new spectrum allocation is shown in Fig. 8.2.

In the future, cellular systems must serve both the old mobile units, which operate 666 channels, and the new mobile units, which operate 832 channels. The new mobile units will have less blocked calls then the old mobile units when they are used in areas of heavy traffic. However, because the additional spectra for bands A and B are discretely and alternately allocated, the neighboring channels between bands A and B occur at two points (one point between channels 666 and 667, and the other between channels 716 and 717) in the frequency spectrum. At these two points, the tendency for neighboring-channel interference is high.

According to the analysis given in Sec. 7.3.1, the "neighboring channels" can consist of four channels on each side of two systems. Therefore, these eight channels must be used with extreme caution. Unless we know the frequency channel assignments of the other system, or coordinate with the other system, it is not wise to use these channels.

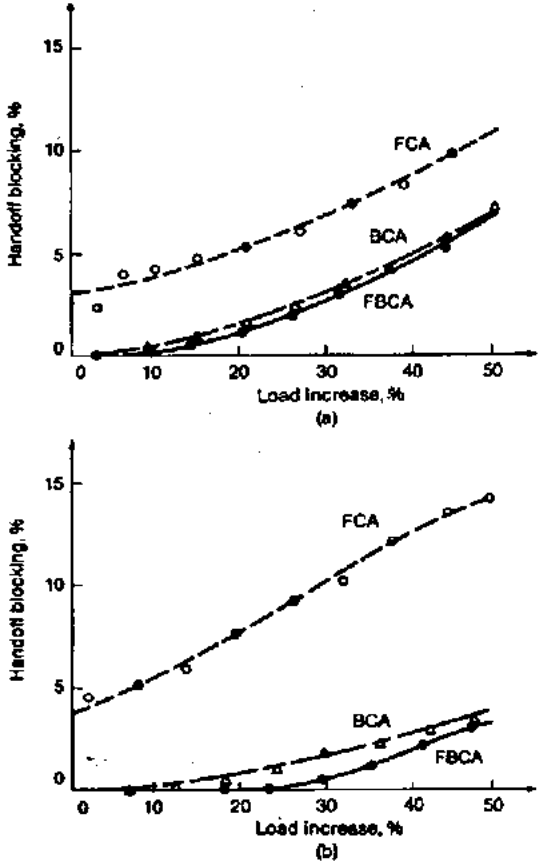


Figure 8.9 Comparison of handoff blocking from three different schemes. (*After Sekiguchi et al., Ref. 9*) (*a*) Handoff blocking in spatially uniform traffic distribution (*b*) handoff blocking in spatially nonuniform traffic distribution.

The ratio of the new additional spectrum to the present spectrum is 5/20 MHz = 25 percent, which means that the effective increase in the spectrum is 25 percent if we can fully use it.

The new additional spectrum utilization factor η at any given period of time can be calculated from

$$\eta = \frac{B}{A + B}$$

where A is the number of customers who are using old mobile units and B is the number of customers using new mobile units. If B is increasing very slowly, then η can be very small. This would defeat the purpose of implementing the new additional spectrum. Therefore, the new mobile units should outdate the old mobile units such that A remains the same and B is increasing. Assume that the number of new subscribers per year is

$$\frac{B}{A} = \frac{1}{10}$$

Then the spectrum-utilization factor for the first year that the new system is implemented would be

$$\eta = \frac{0.10A}{A + 0.10A} = 9\%$$

Then for the second year, the B/A ratio would be

$$\frac{B}{A} = \frac{1}{5}$$

and the spectrum-utilization factor η would be

$$\eta = \frac{0.2A}{A + 0.2A} = 17\%$$

These calculations are based on the assumption that new mobile units are assigned only to new additional channels so that the traffic capacity using the old spectrum will not worsen. After η exceeds 20 percent, the new mobile units have to be assigned to all the 395 voice channels. Implementation of the new additional spectrum is discussed further in Chap. 10.

8.8 Traffic and Channel Assignment

The vehicular traffic density of a coverage area is a critical element and must be determined before a system is designed. This traffic pattern in busy hours can be confined to different zones within the service area. This traffic-density information should be converted to the number of cars per 1000- × 1000-ft grid (or 2000- × 2000-ft grid) and stored in the grids of the contour map provided in Sec. 4.7.

If the traffic pattern predominates over the simple signal coverage pattern, cell-site selection will be based on the traffic pattern.

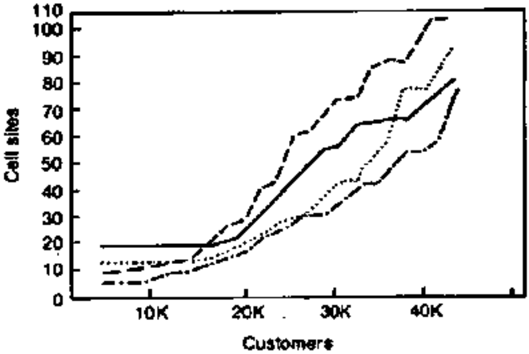


Figure 8.10 City-to-city variation. *(After Whitehead, Ref. 1.)*

Choice of the initial cell sites should be based on the signal covered in zones of heavy vehicular traffic. This means that the cell site would most likely be located at the center of those zones.

After call traffic data are collected while the system is operating, we can update the call traffic data at each cell site to correlate with the vehicular traffic data. This information will be useful for determining whether new cell splitting is needed. If it is, then we must determine how many radios should be installed at the new site and where it is to be located. These decisions are all related to frequency channel assignment. A typical chart illustrating the variation from city to city is shown in Fig. 8.10. A city may have twice as many cell sites to handle the same number of customers in the busy hours. This means that the number of cars per unit area is much higher in one city than that in the other city. Many techniques for implementing the high-capacity cellular systems are discussed in Chap. 10.

8.9 Perception of Call Blocking from the Subscribers

The regular blocked calls are counted when those calls are requested through the setup channel but no voice channels are available. If the setup channel is very busy or has poor coverage, the calls then can not be got through the setup channel. In the cases, the system operator does not know those unrecorded dropped calls. However as the subscribers are concerned, those calls are also blocked calls and named setup channel blockage in Sec. 13.1.1.

References

1. J. F. Whitehead, "Cellular Spectrum Efficiency Via Reuse Planning," *35th IEEE Vehicular Technology Conference Record,* May 21–23, 1985, Boulder, Colorado, pp. 16–20.
2. S. W. Halpern, "Reuse Partitioning in Cellular Systems," *Conference Record of the 33rd IEEE VTS Conference,* May 1983.
3. D. L. Huff, "AT&T Cellular Technology Review," *Conference Record of 1985 IEEE Military Communications Conference,* October 1985, Boston, pp. 490–494.
4. V. H. MacDonald, "The Cellular Concept," *Bell System Technical Journal,* Vol. 58, No. 1, January 1979, pp. 15–42.
5. D. C. Cox and D. O. Reudink, "Increasing Channel Occupancy in Large-Scale Mobile Radio Systems: Dynamic Channel Reassignment," IEEE *Transactions on Vehicular Technology,* Vol. VT-22, November 2, 1973, pp. 218–222.
6. L. G. Anderson, "A Simulation Study of Some Dynamic Channel Assignment Algorithms in a High Capacity Mobile Telecommunications System," *IEEE Transactions on Vehicular Technology,* Vol. VT-22, November 1973, pp. 210–217.
7. T. J. Kahwa and N. D. Georganas, "A Hybrid Channel Assignment Scheme in Large-Scale, Cellular-Structured Mobile Communication Systems," *IEEE Transactions on Communication,* Vol. COM-26, April, 1978, pp. 432–438.
8. G. Nehme and N. D. Georganas, "A Simulation Study of High-Capacity Cellular Land-Mobile Radio-Communication Systems," *Canadian Electrical Engineering Journal,* Vol. 7, No. 1, 1982, pp. 36–39.
9. H. Sekiguchi, H. Ishikawa, M. Koyama, and H. Sawada, "Techniques for Increasing Frequency Spectrum Utilization in Mobile Radio Communication Systems," *35th IEEE Vehicular Technology Conference Record,* Boulder, Colorado, May 21–23, 1985, pp. 26–31.

Chapter

9

Handoffs and Dropped Calls

9.1 Value of Implementing Handoffs

9.1.1. Why handoffs[1-5]

Once a call is established, the set-up channel is not used again during the call period. Therefore, handoff is always implemented on the voice channel. The value of implementing handoffs is dependent on the size of the cell. For example, if the radius of the cell is 32 km (20 mi), the area is 3217 km^2 (1256 mi^2). After a call is initiated in this area, there is little chance that it will be dropped before the call is terminated as a result of a weak signal at the coverage boundary. Then why bother to implement the handoff feature? Even for a 16-km radius cell handoff may not be needed. If a call is dropped in a fringe area, the customer simply redials and reconnects the call.

Handoff is needed in two situations where the cell site receives weak signals from the mobile unit: (1) at the cell boundary, say, −100 dBm, which is the level for requesting a handoff in a noise-limited environment; and (2) when the mobile unit is reaching the signal-strength holes (gaps) within the cell site as shown in Fig. 9.1.

9.1.2 Two types of handoff

There are two types of handoff: (1) that based on signal strength and (2) that based on carrier-to-interference ratio. The handoff criteria are different for these two types. In type 1, the signal-strength threshold level for handoff is −100 dBm in noise-limited systems and −95 dBm in interference-limited systems. In type 2, the value of C/I at the cell boundary for handoff should be 18 dB in order to have toll quality voice. Sometimes, a low value of C/I may be used for capacity reasons.

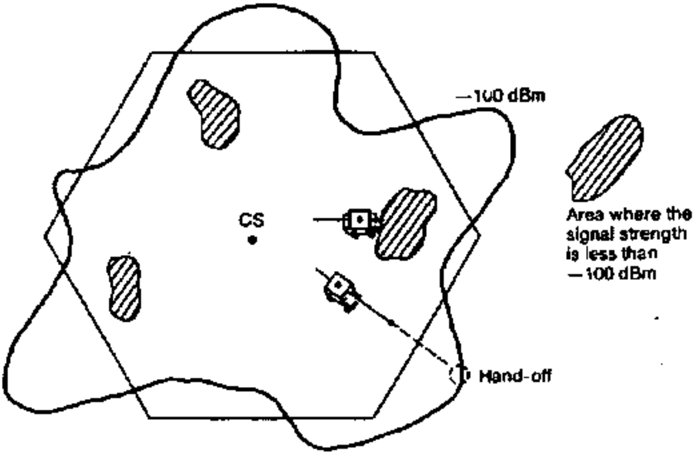


Figure 9.1 Occurrence of handoff.

Type 1 is easy to implement. The location receiver at each cell site measures all the signal strengths of all receivers at the cell site. However, the received signal strength (RSS) itself includes interference.

$$\mathrm{RSS} = C + I \qquad (9.1\text{-}1)$$

where C is the carrier signal power and I is the interference. Suppose that we set up a threshold level for RSS; then, because of the I, which is sometimes very strong, the RSS level is higher and far above the handoff threshold level. In this situation handoff should theoretically take place but does not. Another situation is when I is very low but RSS is also low. In this situation, the voice quality usually is good even though the RSS level is low, but since RSS is low, unnecessary handoff takes place. Therefore it is an easy but not very accurate method of determining handoffs. Some systems use SAT information together with the received signal level to determine handoffs (Sec. 13.1.2).

Handoffs can be controlled by using the carrier-to-interference ratio C/I, which can be obtained as described in Sec. 6.3.

$$\frac{C + I}{I} \approx \frac{C}{I} \qquad (9.1\text{-}2)$$

In Eq. (9.1-2), we can set a level based on C/I, so C drops as a function of distance but I is dependent on the location. If the handoff is dependent on C/I, and if the C/I drops, it does so in response to increase in (1) propagation distance or (2) interference. In both cases, handoff

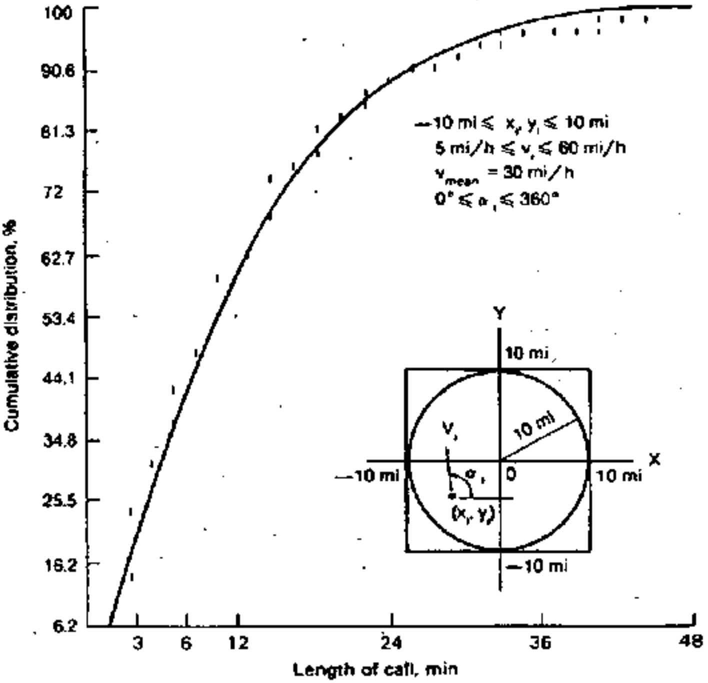


Figure 9.2 The probability of requiring handoff.

should take place. In today's cellular systems, it is hard to measure C/I during a call because of analog modulation. Sometimes we measure the level I before the call is connected, and the level $C + I$ during the call. Thus $(C + I)/I$ can be obtained. Another method of measuring C/I is described in Sec. 6.3. Pg - 192

9.1.3 Determining the probability of requirement for handoffs[6]

To find the probability of requiring a handoff, we can carry out the following simulation. Suppose that a mobile unit randomly initiates a call in a 16-km (10-mi) cell. The vehicle speed is also randomly chosen between 8 and 96 km/h (5 to 60 mi/h). The direction is randomly chosen to be between 0 and 360°; then the chance of reaching the boundary is dependent on the call holding time.

Figure 9.2 depicts the probability curve for requiring handoff. Table 9.1 summarizes the results. If the call holding time is 1.76 min, the only chance of reaching the boundary is 11 percent, or the chance that a handoff will occur for the call is 11 percent. If the call holding time

TABLE 9.1 Probability of Having a Handoff in a 10-mi Coverage Area

Handoff probability, %	Call length, min
11.3	1.76
18	3
42.6	6
59.3	9

is 3 min, the chance of reaching the boundary is 18 percent. Now we may debate whether a handoff is needed or not. In rural areas, handoffs may not be necessary. However, commercial mobile units must meet certain requirements, and handoffs may be necessary at times. Military mobile systems may opt not to use the handoff feature and may apply the savings in cost to implement other security measures.

9.1.4 Number of handoffs per call

The smaller the cell size, the greater the number and the value of implementing handoffs. The number of handoffs per call is relative to cell size. From the simulation, we may find

0.2 handoff per call in a 16- to 24-km cell

1–2 handoffs per call in a 3.2- to 8-km cell

3–4 handoffs per call in a 1.6-to 3.2-km cell

9.2 Initiation of a Handoff

At the cell site, signal strength is always monitored from a reverse voice channel. When the signal strength reaches the level of a handoff (higher than the threshold level for the minimum required voice quality), then the cell site sends a request to the mobile telephone switching level (MTSO) for a handoff on the call. An intelligent decision can also be made at the cell site as to whether the handoff should have taken place earlier or later. If an unnecessary handoff is requested, then the decision was made too early. If a failure handoff occurs, then a decision was made too late.

The following approaches are used to make handoffs successful and to eliminate all unnecessary handoffs. Suppose that −100 dBm is a threshold level at the cell boundary at which a handoff would be taken. Given this scenario, we must set up a level higher than −100 dBm—say, −100 dBm + Δ dB—and when the received signal reaches this level, a handoff request is initiated. If the value of Δ is fixed and large, then the time it takes to lower −100 dBm + Δ to −100 dBm is [illegible] longer. During this time, many situations, such as the mobile unit turning back toward the cell site or stopping, can occur as a result of the direction and the speed of the moving vehicles. Then the signals will never drop below −100 dBm. Thus, many unnecessary handoffs may occur simply because we have taken the action too early. If Δ is small, then there is not enough time for the call to hand off at the cell site and many calls can be lost while they are handed off. Therefore, Δ should be varied according to the path-loss slope of the received signal strength (Sec. 4.2) and the level-crossing rate (LCR) of the signal strength (Sec. 1.63) as shown in Fig. 9.3.

Let the value of Δ be 10 dB in the example given in the preceding paragraph. This would mean a level of −90 dBm as the threshold level for requesting a handoff. Then we can calculate the velocity V of the mobile unit based on the predicted LCR[7] at a −10-dB level with respect to the root-mean-square (rms) level, which is at −90 dBm; thus

$$V = \begin{cases} \dfrac{n\lambda}{\sqrt{2\pi}\,(0.27)} & \text{ft/s} \\ n\lambda & \text{mi/h} \end{cases} \qquad \text{at } -10\text{-dB level} \qquad (9.2\text{-}1)$$

where n is the LCR (crossings per second) counting positive slopes and λ is the wavelength in feet. Equation (9.2-1) can be simplified as

$$V(\text{mi/h}) \approx n(\text{crossings/s}) \text{ at 850 MHz and a } -10\text{-dB level} \qquad (9.2\text{-}2)$$

Here, two pieces of information, the velocity of vehicle V and the path-loss slope γ, can be used to determine the value of Δ dynamically so that the number of unnecessary handoffs can be reduced and the required handoffs can be completed successfully.

There are two circumstances where handoffs are necessary but cannot be made: (1) when the mobile unit is located at a signal-strength hole within a cell but not at the boundary (see Fig. 9.3) and (2) when the mobile unit approaches a cell boundary but no channels in the new cell are available.

In case 1, the call must be kept in the old frequency channel until it is dropped as the result of an unacceptable signal level. In case 2, the new cell must reassign one of its frequency channels within a reasonably short period or the call will be dropped.

The MTSO usually controls the frequency assignment in each cell and can rearrange channel assignments or split cells when they are necessary. Cell splitting is described in Sec. 10.4.

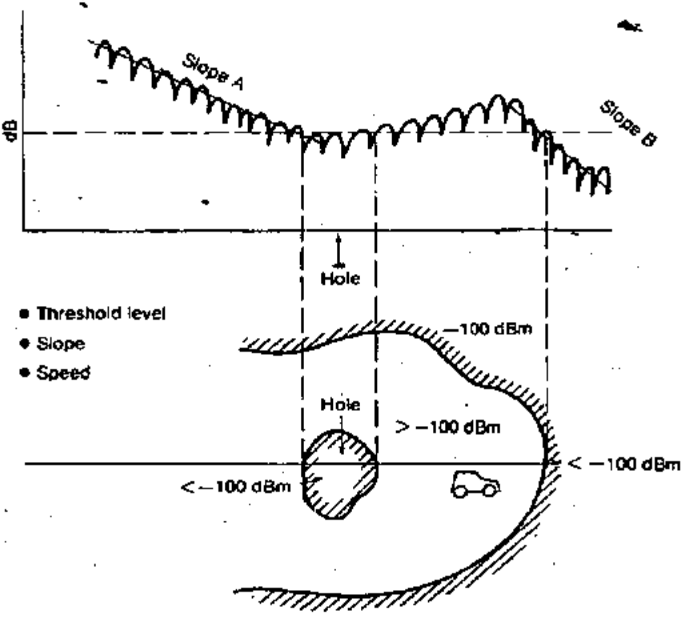


Figure 9.3 Parameters for handling a handoff.

9.3 Delaying a Handoff

9.3.1 Two-handoff-level algorithm

In many cases, a two-handoff-level algorithm is used. The purpose of creating two request handoff levels is to provide more opportunity for a successful handoff. A handoff could be delayed if no available cell could take the call.

A plot of signal strength with two request handoff levels and a threshold level is shown in Fig. 9.4. The plot of average signal strength is recorded on the channel received signal-strength indicator (RSSI) which is installed at each channel receiver at the cell site. When the signal strength drops below the first handoff level, a handoff request is initiated. If for some reason the mobile unit is in a hole (a weak spot in a cell) or a neighboring cell is busy, the handoff will be requested periodically every 5 s. At the first handoff level, the handoff takes place if the new signal is stronger (see case I in Fig. 9.4). However, when the second handoff level is reached, the call will be handed off with no condition (see case II in Fig. 9.4).

The MTSO always handles the handoff call first and the originating calls second. If no neighboring calls are available after the second

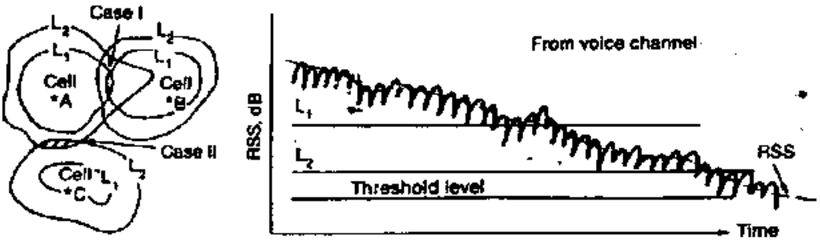


Figure 9.4 A two-level handoff scheme.

handoff level is reached, the call continues until the signal strength drops below the threshold level; then the call is dropped. If the supervisory audio tone (SAT) is not sent back to the cell site by the mobile unit within 5 s, the cell site turns off the transmitter.

SAT = supervisory Audiotone.

9.3.2 Advantage of delayed handoffs

Consider the following example. The mobile units are moving randomly and the terrain contour is uneven. The received signal strength at the mobile unit fluctuates up and down. If the mobile unit is in a hole for less than 5 s (a driven distance of 140 m for 5 s, assuming a vehicle speed of 100 km/h), the delay (in handoff) can even circumvent the need for a handoff.

If the neighboring cells are busy, delayed handoff may take place. In principle, when call traffic is heavy, the switching processor is loaded, and thus a lower number of handoffs would help the processor handle call processing more adequately. Of course, it is very likely that after the second handoff level is reached, the call may be dropped with great probability.

The other advantage of having a two-handoff-level algorithm is that it makes the handoff occur at the proper location and eliminates possible interference in the system. Figure 9.4, case I, shows the area where the first-level handoff occurs between cell A and cell B. If we only use the second-level handoff boundary of cell A, the area of handoff is too close to cell B. Figure 9.4, case II, also shows where the second-level handoff occurs between cell B and cell C. This is because the first-level handoff cannot be implemented.

9.4 Forced Handoffs

A *forced handoff* is defined as a handoff which would normally occur but is prevented from happening, or a handoff that should not occur but is forced to happen.

9.4.1 Controlling a handoff

The cell site can assign a low handoff threshold in a cell to keep a mobile unit in a cell longer or assign a high handoff threshold level to request a handoff earlier. The MTSO also can control a handoff by making either a handoff earlier or later, after receiving a handoff request from a cell site.

9.4.2 Creating a handoff

In this case, the cell site does not request a handoff but the MTSO finds that some cells are too congested while others are not. Then the MTSO can request cell sites to create early handoffs for those congested cells. In other words, a cell site has to follow the MTSO's order and increase the handoff threshold to push the mobile units at the new boundary and to hand off earlier.

9.5 Queuing of Handoffs

Queuing of handoffs is more effective than two-threshold-level handoffs. The MTSO will queue the requests of handoff calls instead of rejecting them if the new cell sites are busy. A queuing scheme becomes effective only when the requests for handoffs arrive at the MTSO in batches or bundles. If handoff requests arrive at the MTSO uniformly, then the queuing scheme is not needed. Before showing the equations, let us define the parameters as follows.

$1/\mu$	average calling time in seconds, including *new calls* and *handoff calls* in each cell
λ_1	arrival rate (λ_1 calls per second) for originating calls
λ_2	arrival rate (λ_2 handoff calls per second) for handoff calls
M_1	size of queue for originating calls
N	number of voice channels
a	$(\lambda_1 + \lambda_2)/\mu$
b_1	λ_1/μ
b_2	λ_2/μ

The following analysis can be used to see the improvement. We are analyzing three cases.[8]

1. *No queuing on either the originating calls or the handoff calls.* The blocking for either an originating call or a handoff call is

$$B_o = \frac{a^N}{N!} P(0) \checkmark \tag{9.5-1}$$

where

$$P(0) = \left(\sum_{n=0}^{N} \frac{a^N}{n!} \right)^{-1} \tag{9.5-2}$$

2. *Queuing the originating calls but not the handoff calls.* The blocking probability for originating calls is

$$B_{oq} = \left(\frac{b_1}{N}\right)^{M_1} P_q(0) \checkmark \tag{9.5-3}$$

where

$$P_q(0) = \left[N! \sum_{n=0}^{N-1} \frac{a^{n-N}}{n!} + \frac{1 - (b_1/N)^{M_1+1}}{1 - (b_1/N)} \right]^{-1} \tag{9.5-4}$$

The blocking probability for handoff calls is

$$B_{oh} = \frac{1 - (b_1/N)^{M_1+1}}{1 - (b_1/N)} P_q(0) \checkmark \tag{9.5-5}$$

3. *Queuing the handoff calls but not the originating calls.* The blocking probability for handoff calls is

$$B_{hq} = \left(\frac{b_2}{N}\right)^{M_2} P_q(0) \tag{9.5-6}$$

where $P_q(0)$ is as shown in Eq. (9.5-4). The blocking probability for originating calls is

$$B_{ho} = \frac{1 - (b_2/N)^{M_2+1}}{1 - (b_2/N)} P_q(0) \tag{9.5-7}$$

Example 9.1 The following parameters are given. The number of channels at the cell site $N = 70$. The call holding time is 101 s = 0.028 h. The number of originating calls attempted per hour is expressed as $\lambda_1 = 2270$. The number of handoff calls attempted per hour is expressed as $\lambda_2 = 80$. Then

$$A = \frac{\lambda + \lambda_2}{\mu} = (2270 + 80)\,0.028 = 65.80$$

$$b_1 = \frac{\lambda_1}{\mu} = 2270 \times 0.028 = 63.60$$

$$b_2 = \frac{\lambda_2}{\mu} = 2.24$$

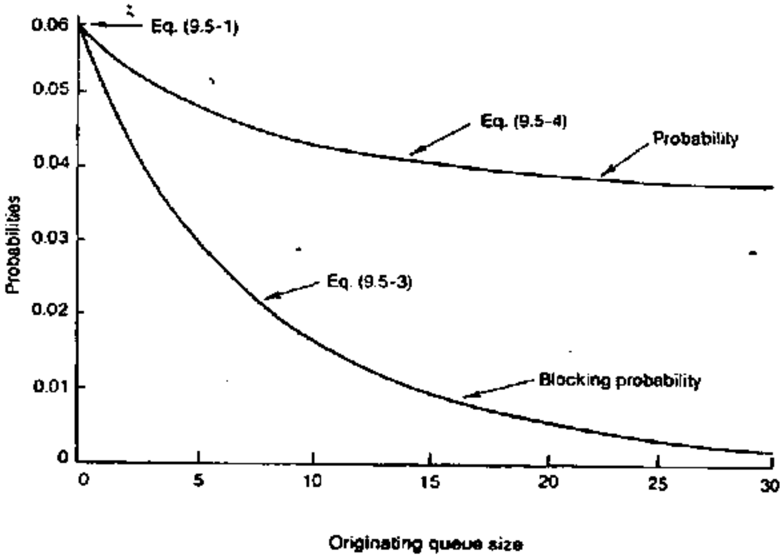


Figure 9.6 Probability and blocking probability graph showing blocking probability for originating calls (queuing for originating calls) ($N = 70$).

Given these parameters, Eqs. (9.5-1), (9.5-3), (9.5-5), (9.5-6), and (9.5-7) have been plotted in Figs. 9.5, 9.6, 9.7, and 9.8 respectively.

We have seen (Figs. 9.5 and 9.6) with queuing of originating calls only, the probability of blocking is reduced. However, queuing of originating calls results in increased blocking probability on handoff calls, and this is a drawback. With queuing of handoff calls only, blocking probability is reduced from 5.9 to 0.1 percent by using one queue space (see Fig. 9.7). Therefore it is very worthwhile to implement a simple queue (one space) for handoff calls. Adding queues in handoff calls does not affect the blocking probability of originating calls in this particular example (see Fig. 9.8). However, we should always be aware that queuing for the handoff is more important than queuing for those initiating calls on assigned voice channels because call drops upset customers more than call blockings.

9.6 Power-Difference Handoffs

A better algorithm is based on the power difference (Δ) of a mobile signal received by two cell sites, home and handoff. Δ can be positive or negative. The handoff occurs depending on a preset value of Δ.

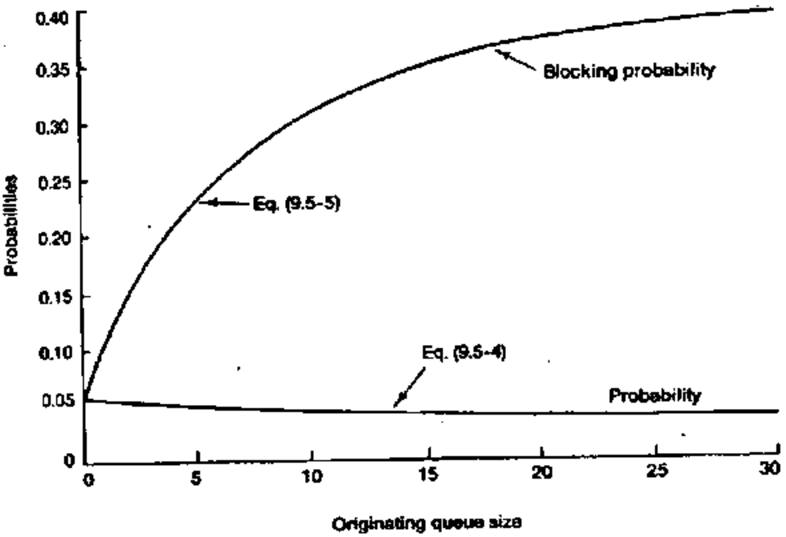


Figure 9.6 Probability and blocking probability graph showing blocking probability for handoff calls (queuing for originating calls) ($N = 70$).

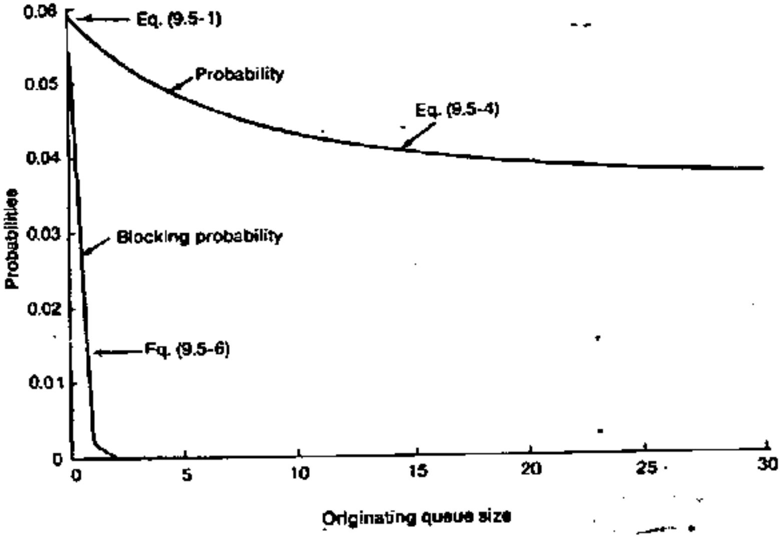


Figure 9.7 Probability and blocking probability graph showing blocking probability for handoff calls (queuing for handoff calls)($N = 70$).

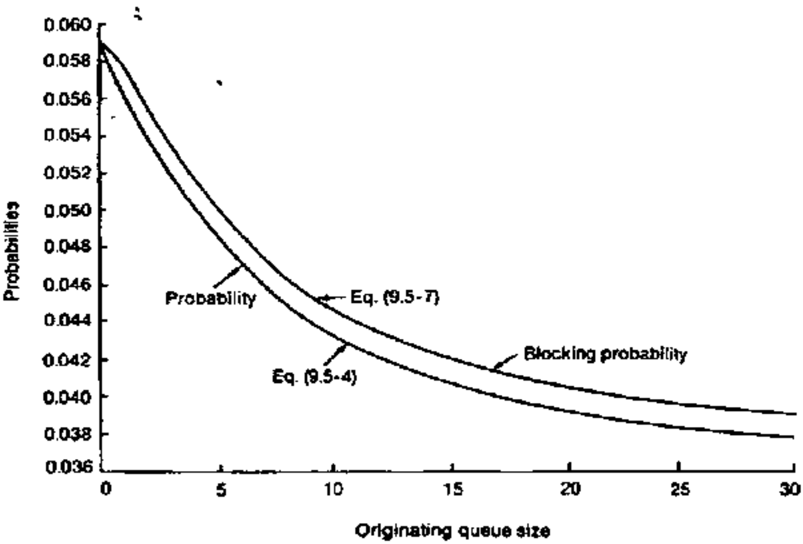


Figure 9.8 Probability and blocking probability graph showing blocking probability for originating calls (queuing for handoff calls) ($N = 70$).

★
$$\Delta = \text{the mobile signal measured at the candidate handoff site} - \text{the mobile signal measured at the home site} \quad (9.6\text{-}1)$$

For example, the following cases can occur.

$\Delta > 3$ dB	request a handoff
$1 \text{ dB} < \Delta < 3$ dB	prepare a handoff
$-3 \text{ dB} < \Delta < 0$ dB	monitoring the signal strength
$\Delta < -3$ dB	no handoff

Those numbers can be changed to fit the switch processor capacity. This algorithm is not based on the received signal strength level, but on a relative (power difference) measurement. Therefore, when this algorithm is used, all the call handoffs for different vehicles can occur at the same general location in spite of different mobile antenna gains or heights.

9.7 Mobile Assisted Handoff (MAHO) and Soft Handoff

In a normal handoff procedure, the request for a handoff is based on the signal strength or the SAT range of a mobile signal received at the cell site from the reverse link. In the digital cellular system, the mobile receiver is capable of monitoring the signal strength of the setup channels of the neighboring cells while serving a call. For instance, in a TDMA system, one time slot is used for serving a call, the rest of the time slots can be used to monitor the signal strengths of setup channels. When the signal strength of its voice channel is weak, the mobile unit can request a handoff and indicate to the switching office which neighboring cell can be a candidate for handoff. Now the switching office has two peices of information, the signal strengths of both forward and reverse setup channels, of a neighboring cell or two different neighboring cells. The switching office, therefore, has more intelligent information to choose the proper neighboring cell to handoff to.

The soft handoff is applied to one kind of digital cellular system named CDMA. In CDMA systems, all cells can use the same radio carrier. Therefore, the frequency reuse factor K approaches one. Since the operating radio carriers of all cells are the same, no need to change from one frequency to another frequency but change from one code to another code. Thus there is no hard handoff. We call this kind of handoff a soft handoff. If sometimes there are more than one CDMA radio carrier operating in a cell, and if the soft handoff from one cell to another is not possible for some reason, the intra-cell hard handoff may take place first, then go to the inter-cell soft handoff.

9.8 Cell-Site Handoff Only

This scheme can be used in a noncellular system. The mobile unit has been assigned a frequency and talks to its home cell site while it travels. When the mobile unit leaves its home cell and enters a new cell, its frequency does not change; rather, the new cell must tune into the frequency of the mobile unit (see Fig. 9.9). In this case only the cell sites need the frequency information of the mobile unit. Then the aspects of mobile unit control can be greatly simplified, and there will

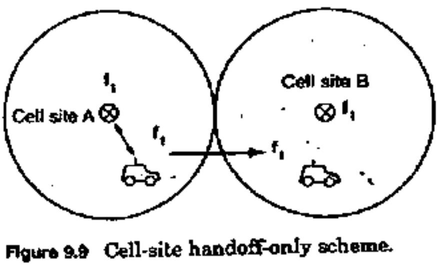


Figure 9.9 Cell-site handoff-only scheme.

be no need to provide handoff capability at the mobile unit. The cost will also be lower.

This scheme can be recommended only in areas of very low traffic. When the traffic is dense, frequency coordination is necessary for the cellular system. Then if a mobile unit does not change frequency on travel from cell to cell, other mobile units then must change frequency to avoid interference.

Therefore, if a system handles only low volumes of traffic, that is, if the channels assigned to one cell will not reuse frequency in other cells, then it is possible to implement the cell-site handoff feature as it is applied in military systems.

9.9 Intersystem Handoff

Occasionally a call may be initiated in one cellular system (controlled by one MTSO) and enter another system (controlled by another MTSO) before terminating. In some instances, *intersystem handoff* can take place; this means that a call handoff can be transferred from one system to a second system so that the call be continued while the mobile unit enters the second system.

The software in the MTSO must be modified to apply this situation. Consider the simple diagram shown in Fig. 9.10. The car travels on a highway and the driver originates a call in system A. Then the car

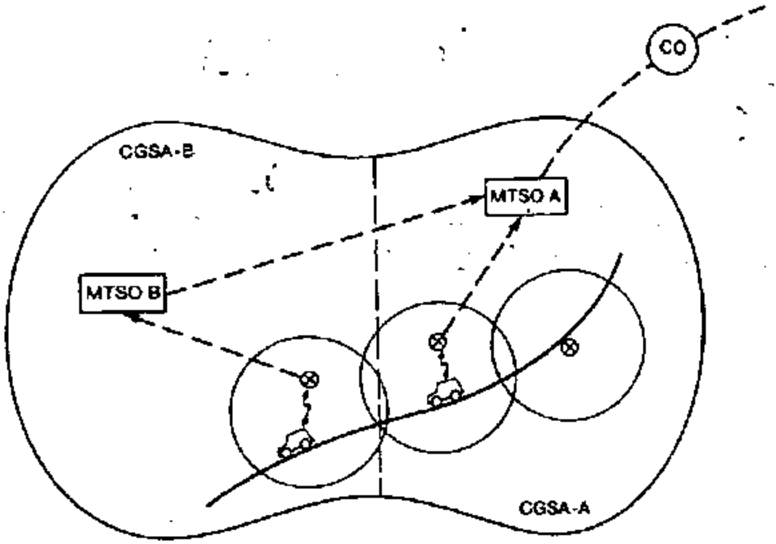


Figure 9.10 Intersystem handoffs.

leaves cell site A of system A and enters cell site B of system B. Cell sites A and B are controlled by two different MTSOs. When the mobile unit signal becomes weak in cell site A, MTSO A searches for a candidate cell site in its system and cannot find one. Then MTSO A sends the handoff request to MTSO B through a dedicated line between MTSO A and MTSO B, and MTSO B makes a complete handoff during the call conversation. This is just a one-point connection case. There are many ways of implementing intersystem handoffs, depending on the actual circumstances. For instance, if two MTSOs are manufactured by different companies, then compatibility must be determined before implementation of intersystem handoff can be considered. A detailed discussion of this topic appears in Sec. 11.4.

9.10 Introduction to Dropped Call Rate

The definition of dropped call rate. The definition of a dropped call is after the call is established but before it is properly terminated. The definition of "the call is established" means that the call is setup completely by the setup channel. If there is a possibility of a call drop due to no available voice channels, this is counted as a blocked call not a dropped call.

If there is a possibility that a call will drop due to the poor signal of the assigned voice channel, this is considered a dropped call. This case can happen when the mobile or portable units are at a standstill and the radio carrier is changed from a strong setup channel to a weak voice channel due to the selective frequency fading phenomenon.

The perception of dropped call rate by the subscribers can be higher due to:

1. The subscriber unit not functioning properly (needs repair).
2. The user operating the portable unit in a vehicle (misused).
3. The user not knowing how to get the best reception from a portable unit (needs education).

Consideration of dropped calls. In principle, dropped call rate can be set very low if we do not need to maintain the voice quality. The dropped call rate and the specified voice quality level are inversely proportional. In designing a commercial system, the specified voice quality level is given relating to how much C/I (or C/N) the speech coder can tolerate. By maintaining a certain voice quality level, the dropped call rate can be calculated by taking the following factors into consideration:

1. Provide signal coverage based on the percentage (say 90%) that all the received signal will be above a given signal level.
2. Maintain the specified co-channel and adjacent channel interference levels in each cell during a busy hour, i.e., the worst interference case.
3. Since the performance of the call dropped rate is calculated as possible call dropping in every stage from the radio link to the PSTN connection, the response time of the handoff in the network will be a factor when the cell becomes small, the response time for a handoff request has to be shorter in order to reduce the call dropped rate.
4. The signaling of the handoff and the MAHO algorithm will also impact the call dropped rate.
5. The relationship among the voice quality, system capacity and call dropped rate can be expressed through a common parameter C/I.

Relationship among capacity, voice quality, dropped call rate. Radio Capacity m is expressed as follows:

$$m = \frac{B_T/B_c}{\sqrt{\frac{2}{3}(C/I)_S}} \qquad (9.10\text{-}1)$$

where B_T/B_c is the total number of voice channels. B_T/B_c is a given number, and $(C/I)_S$ is a required C/I for designing a system. The above equation is obtained based on six co-channel interferers which occur in busy traffic, i.e., a worst case. In an interference limited system, the adjacent channel interference has only a secondary effect. The derivation of Eq. (9.10-1) will be expressed in Chap. 13. Eq. (9.10-1) can be changed to the following form:

$$(C/I)_S = \frac{3}{2}\left(\frac{B_T/B_c}{m}\right)^2 = \frac{3}{2}\left(\frac{B_T}{B_c}\right)^2 \cdot \frac{1}{m^2} \qquad (9.10\text{-}2)$$

Since the $(C/I)_S$ is a required C/I for designing a system, the voice quality is based on the $(C/I)_S$. When the specified $(C/I)_S$ is reduced, the radio capacity is increased. When the measured (C/I) is less than the specified $(C/I)_S$, both poor voice quality and dropped calls can occur.

Coverage of 90% equal-strength contour. The coverage in cellular cells always uses the coverage of 90% equal-strength contour. The prediction tool (Lee Model) described in Chap. 4 is used to predict the equal-strength contour at level C with 50% time and 50% area in a cell. For example, let $C = -102$ dBm, which is 18 dB above the ambient noise -120 dBm. If $C = -102$ dBm is 50% equal-strength contour, then increase the level to $C + 10$ dB contour which can be calculated from the following equation:

$$P(x' < A) = \int_{-\infty}^{A} \frac{1}{\sqrt{2\pi}\sigma} \exp\left[\frac{(y' - \overline{m})^2}{2\sigma^2}\right] dy'$$

$$= P\left(x < \frac{A - \overline{m}}{\sigma}\right) \qquad (9.10\text{-}3)$$

Eq. (9.10-3) is the cumulative distribution function where A is the desired signal level and $\overline{m}$ is the mean level. σ is long-term fading due to terrain contour. If $A = C + 10 = -92$ dB and $\sigma = 8$ dB:

$$S = P\left(x < \frac{-92 - (-102)}{8}\right) = P\left(x < \frac{10}{8}\right) = 0.9082 \qquad (9.10\text{-}4)$$

Eq. (9.10-4) can also be interpreted as being at a -92 dBm contour, the signal above the level of -102 dBm is 90.8%. Of course, the level of -102 dBm is determined to be 18 dB above -120 dBm which is the ambient noise level. The $(C/N)_S$ of 18 dB is the required level for getting a voice quality.

9.11 Formula of Dropped Call Rate

The dropped call rate can be calculated either using general formula or by a commonly used formula.

General formula of dropped call rate. The general formula of dropped call rate P in a whole system can be expressed as:

$$P = 1 - \left[\sum_{n=0}^{N} \alpha_n X^n\right] = \sum_{n=0}^{N} \alpha_n \cdot P_n \qquad (9.11\text{-}1)$$

where

$$P_n = (1 - X^n) \qquad (9.11\text{-}2)$$

P_n is the probability of a dropped call ~~when the call~~ has gone through n handoffs and

$$X = (1 - \delta)(1 - \mu)(1 - \theta\nu)(1 - \beta)^2 \qquad (9.11\text{-}3)$$

δ = Probability that the signal is below the specified receive threshold (in a noise-limited system).

μ = Probability that the signal is below the specified cochannel interference level (in an interference-limited system).

τ = Probability that no traffic channel is available upon handoff attempt when moving into a new cell.

θ = Probability that the call will return to the original cell.

β = Probability of blocking circuits between BSC and MSC during handoff.

α_n = The weighted value for those calls having n handoffs, and $\Sigma_{n=0}^{N} \alpha_n = 1$

N = N is the highest number of handoffs for those calls.

Eq. (9.11-3) needs to be explained clearly as follows:

(1) z_1 and z_2 are two events, z_1 is the case of no traffic channel in the cell, z_2 is the case of no-safe return to original cell. Assuming that z_1 and z_2 are independent events, then

$$P(z_2|z_1) \cdot P(z_1) = P(z_1) \cdot P(z_1) = \theta \cdot \tau$$

(2) $(1 - \beta)$ is the probability of a call successfully connecting from the old BSC to the MSC. Also, $(1 - \beta)$ is the probability of a call successfully connecting from the MSC to the new BSC. Then the total probability of having a successful call connection is:

$$\left.\begin{array}{ll}\text{BSC (old)} \rightarrow \text{MSC} & (1 - \beta) \\ \text{MSC} \rightarrow \text{BSC (new)} & (1 - \beta)\end{array}\right\rangle (1 - \beta)^2$$

(3) The call dropped rate P expressed in Eq. (9.11-1) can be specified in two cases:

1. In a noise limited system (startup system): there is no frequency reuse, the call dropped rate P_A is based on the signal coverage. It can also be calculated under busy hour conditions. In a noise-limited environment (for worst case)

$$\delta = \delta_I$$

$$\mu = \mu_I$$

$$\left.\begin{array}{l}\tau = \tau_1 \\ \theta = \theta_1 \\ \beta = \beta_I\end{array}\right\} \text{the conditions for the noise limited case}$$

2. In an interference-limited system (mature system): frequency reuse is applied, and the dropped rate P_B is based on

the interference level. It can be calculated under busy hour conditions.

In an interference-limited environment (for worst case)

$$\delta = \delta_2$$

$$\mu = \mu_1$$

$$\left.\begin{aligned} \tau &= \tau_2 \\ \theta &= \theta_2 \\ \beta &= \beta_2 \end{aligned}\right\} \text{the conditions for the interference limited case}$$

Eq. (9.11-1) has to make a distinguished difference between P_A and P_B. The cases of P_A and P_B do not occur at the same time. When capacity is based on frequency reuse, the interference level is high, the size of the cells is small, and coverage is not an issue. The call dropped rate totally depends on interference.

Commonly used formula of dropped call rate. In a commonly used formula of dropped call rate, the values of τ, θ, and β are assumed to be very small and can be neglected. Then Eq. (9.11-3) becomes:

$$X = (1 - \delta)(1 - \mu) \tag{9.11-4}$$

Furthermore, in a noise-limited case, $\mu \to 0$, Eq. (9.11-1) becomes:

$$P_A = \sum_{n=0}^{N} \alpha_n P_n = \sum \alpha_n [1 - (1 - \delta)^n] \tag{9.11-5}$$

and in an interference-limited system, $\delta \to 0$, Eq. (9.11-1) becomes:

$$P_B = \sum_{n=0}^{N} \alpha_n P_n = \sum \alpha_n [1 - (1 - \mu)^n] \tag{9.11-6}$$

Handoff distribution of calls, α_n. The α_n is the weight value for those calls having n handoffs. Then the handoff distribution of all α_n's is needed for calculating Eq. (9.11-1), or Eq. (9.11-5), or Eq. (9.11-6). The relationship of all α_n's is:

$$\sum_{n=0}^{N} \alpha_n = 1$$

The handoff distribution of calls α_n can be assumed as follows:

The α_n in macrocells is used for calculating the dropped call rate P_A:

Kinds of Units	n Handoffs Per Call	Percent of Units	α_n
Handset Units	$n = 0$	100%	$\alpha_0 = 1$
Mobile Units	$n = 0$	20%	$\alpha_0 = 0.2$
	$n = 1$	60%	$\alpha_1 = 0.6$
	$n = 2$	20%	$\alpha_2 = 0.2$

The α_n in microcells is used for calculating the dropped call rate P_B:

Kinds of Units	n Handoffs Per Call	Percent of Units	α_n
Handset Units	$n = 0$	80%	$\alpha_0 = 0.8$
	$n = 1$	20%	$\alpha_1 = 0.2$
Mobile Units	$n = 0$	20%	$\alpha_0 = 0.2$
	$n = 1$	60%	$\alpha_1 = 0.6$
	$n = 2$	20%	$\alpha_2 = 0.2$

The values of α_n are used for calculating the dropped call rate. For instance, calculating the general formular of dropped call rate (Eq. (9.11-1)) in macrocells (noise-limited system) for mobile units.

$$P_A = 1 - [0.2X^0 + 0.6X^1 + 0.2X^2]$$

$$= 0.2P_0 + 0.6P_1 + 0.2P_2 \qquad (9.11\text{-}7)$$

where X is expressed in Eq. (9.11-3). In Eq. (9.11-3), the values of τ, θ, and β are usually small. Therefore, the value of X is heavily dependent on δ and μ.

9.12 Finding the Values of δ and μ

The values of δ and μ can be derived for a single cell case and in the case of a handoff. The single cell case solution is used for estimating the blocked calls. The reason behind this is that the probability of δ and μ in a single case is used for the blocked call rate of setting up calls. Assuming that after a call is set up, the call will not be dropped in a cell until the mobile unit travels into the handoff region.

Formula for δ and μ. We first find the value of δ in a single cell by integrating Eq. (9.10-3) over a whole cell to find the area Q in which the measured x will be greater than $A(r) - \overline{m}/\sigma$. The mean value $\overline{m}$ is a specified receive level. A is the signal level which is a function of $A(r)$ that exceeds $\overline{m}$ at the distance r which is less or equal to the cell radius R.

$$Q = \int_0^R P\left(x > \frac{A(r) - \overline{m}}{\sigma}\right) \cdot 2\pi r dr \qquad (9.12\text{-}1)$$

The probability δ that the signal is below a specified receive threshold $\overline{m}$ in a noise-limited environment system is

$$S = \frac{\pi R^2 - Q}{\pi R^2}$$

$$= 1 - \frac{1}{\pi R^2} \int_0^R \left(1 - P\left(x < \frac{A(r) - \overline{m}}{\sigma}\right)\right) \cdot 2\pi r dr \quad (9.12\text{-}2)$$

The probability μ that the signal is below the specified signal level C over the interference level I in an interference-limited system can also be expressed as:

$$\mu = \frac{\pi R^2 - Q}{\pi R^2}$$

$$= 1 - \frac{1}{\pi R^2} \int_0^R \left(1 - P\left(x < \frac{A(r) - C}{\sigma}\right)\right) \cdot 2\pi r \cdot dr \quad (9.12\text{-}3)$$

we may use the numerical calculation to solve Eq. (9.12-2) and Eq. (9.12-3) for dropped calls due to handoffs:

Calculation of δ and μ in a single cell. δ is calculated numerically in a noise-limited case. The cell can be divided into five rings as shown in Fig. 9.11. Eq. (9.12-2), then can be expressed as:

$$\delta = 1 - \frac{\sum_{i=1}^{5} p_i \left(x > \frac{A_i(r_i) - \overline{m}}{\sigma}\right) \cdot a_i}{\pi R^2} \quad (9.12\text{-}4)$$

where

$$1 - P_i\left(x < \frac{A_i(r_i) - \overline{m}}{\sigma}\right) = p_i\left(x > \frac{A_i(r_i) - \overline{m}}{\sigma}\right).$$

$$a_i = \pi[2i - 1]r_1^2$$

$$\sum_{i=1}^{5} a_i = \pi R^2 \quad (9.12\text{-}5)$$

in a single cell. $A_5(r_5 = R)$ is the desired signal level at the cell radius $R = 5r_1$. Let

$$p_i\left(x > \frac{A_i(r_i) - \overline{m}}{\sigma}\right) = p_i$$

for simplicity. Eq. (9.12-4) can also be expressed as:

$$\delta = \frac{\sum_{i=1}^{5} (1 - p_i) \cdot a_i}{\pi R^2} \tag{9.12-6}$$

Eq. (9.12-6) is also the equation for obtaining the value of μ in the interference case.

δ_h and μ_h are improved due to the natural two-site diversity in the handoff region. Due to natural situations providing equivalent two-site diversity in the handoff region, in region a_5, the probability of dropping a call is reduced by $1 - (1 - p_5)^2$ as compared with p_5. In region a_4, the probability of dropping a call is $1 - (1 - p_4)(1 - p_6)$ as compared with p_4. p_6 is the probability of a dropped call due to the fact that the handoff takes place in a_4 by the new cell coverage. Therefore, δ_h and μ_h are expressed as:

$$\left.\begin{matrix}\delta_h\\ \mu_h\end{matrix}\right\} = \frac{(1 - p_5)^2 a_5 + (1 - p_4)(1 - p_6)a_4 + (1 - p_3)a_3 + (1 - p_2)a_2 + (1 - p_1)a_1}{\pi R^2} \tag{9.12-7}$$

Be aware that p_i is the probability of having a successful call and P_i is the probability of a dropped call.

✓**Example 9.1** Given $\sigma = 6$, $\overline{m} = -104$ dBm, $A_5 = -96$ dBm, find the ~~value of~~ δ_h during a handoff? (See Fig. 9.11.)
Based on the 40 dB/dec rule, we can obtain $A_4 = -92$ dBm, $A_3 = -87$ dBm, $A_2 = -80$ dBm, $A_1 = -68$ dBm, $A_6 = -99$ dBm and also

$$p_5\left(x < \frac{-96 - (-104)}{6}\right) = 0.9082,\ p_4 = 0.948,\ p_3 = 0.9977,$$

$$p_2 = 1,\ p_1 = 1,\ p_6 = 0.7967$$

Then applied to Eq. (9.12-7), we obtain

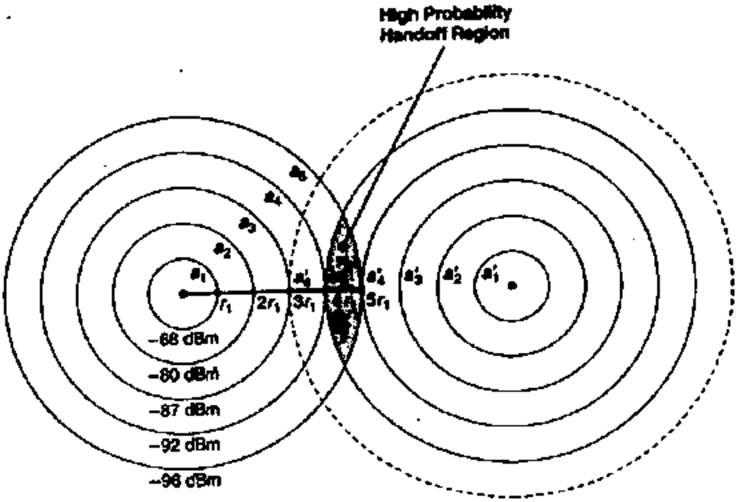


Figure 9.11 The diagram for calculating the dropped calls due to handoffs.

$$\delta_h = \frac{(1-p_5)^2 a_5 + (1-p_4)(1-p_6)a_4 + (1-p_3)a_3 + (1-p_2)a_2 + (1-p_1)a_1}{\pi R^2}$$

$$= 0.64\%$$

Example 9.2 Given $\sigma = 6$, $I = -104$ dBm, $C/I = 12$ dB, and the signal received is requested to be 8 dB above the average C/I, find the value of μ_h during a handoff? Based on the 40 dB/dec rule, $C = -92$ dBm and $A_5 = -84$ dBm, we obtain $A_1 = -50$ dBm, $A_2 = -62$ dBm, $A_3 = -75$ dBm, and $A_4 = -80$ dBm, $A_6 = -87$ dBm. Then applying Eq. (9.12-7), we find:

$$\mu_h = \frac{(1-p_5)^2 a_5 + (1-p_4)(1-p_6)a_4 + (1-p_3)a_3 + (1-p_2)a_2 + (1-p_1)a}{\pi R^2}$$

$$= 1.45\%$$

References

1. "Advanced Mobile Phone Services," Special Issue, *Bell System Technical Journal*, Vol. 58, January 1979.

2. F. H. Blecher, "Advanced Mobile Phone Service," *IEEE Transactions on Vehicular Technology*, Vol. ST-29, May 1980, pp. 238–244.
3. J. Oetting, "Cellular Mobile Radio—an Emerging Technology," *IEEE Communications Magazine*, Vol. 21, No. 8, November 1983, pp. 10–15.
4. V. H. MacDonald, "The Cellular Concept," *Bell System Technical Journal*, Vol. 58, January 1979, pp. 15–43.
5. W. C. Y. Lee, "Elements of Cellular Mobile Radio Systems," *IEEE Transactions on Vehicular Technology*, Vol. VT-35, May 1986, pp. 48–56.
6. W. C. Y. Lee and H. Smith, "A Computer Simulation Model for the Evaluation of Mobile Radio Systems in the Military Tactical Environment," *IEEE Transactions on Vehicular Technology*, Vol. VT-32, May 1983, pp. 177–190.
7. W. C. Y. Lee, *Mobile Communications Design Fundamentals*, Howard W. Sams & Co., 1986, p. 101.
8. D. R. Cox and W. L. Smith, *Queues*, Chapman & Hall Book Co.; 1961, Chap. 2.