Chapter

1

Introduction to Cellular Mobile Systems

1.1 Why Cellular Mobile Telephone Systems?

1.1.1 Limitations of conventional mobile telephone systems

One of many reasons for developing a *cellular* mobile telephone system and deploying it in many cities is the operational limitations of conventional mobile telephone systems: limited service capability, poor service performance, and inefficient frequency spectrum utilization.

Limited service capability. A conventional mobile telephone system is usually designed by selecting one or more channels from a specific frequency allocation for use in autonomous geographic zones, as shown in Fig. 1.1. The communications coverage area of each zone is normally planned to be as large as possible, which means that the transmitted power should be as high as the federal specification allows. The user who starts a call in one zone has to reinitiate the call when moving into a new zone (see Fig. 1.1) because the call will be dropped. This is an undesirable radio telephone system since there is no guarantee that a call can be completed without a handoff capability.

The handoff is a process of automatically changing frequencies as the mobile unit moves into a different frequency zone so that the conversation can be continued in a new frequency zone without redialing. Another disadvantage of the conventional system is that the number of active users is limited to the number of channels assigned to a particular frequency zone.

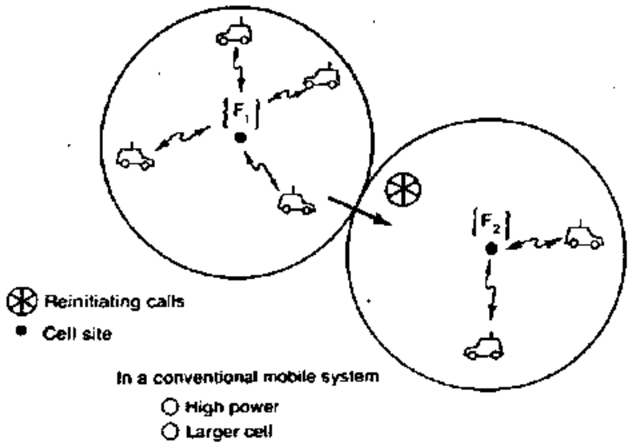


Figure 1.1 Conventional mobile system.

Poor service performance. In the past, a total of 33 channels were allocated to three mobile telephone systems: Mobile Telephone Service (MTS), Improved Mobile Telephone Service (IMTS) MJ systems, and Improved Mobile Telephone Service (IMTS) MK systems. MTS operates around 40 MHz and MJ operates at 150 MHz; both provide 11 channels; IMTS MK operates at 450 MHz and provides 12 channels. These 33 channels must cover an area 50 mi in diameter. In 1976, New York City had 6 channels of MJ serving 320 customers, with another 2400 customers on a waiting list. New York City also had 6 channels of MK serving 225 customers, with another 1300 customers on a waiting list. The large number of subscribers created a high blocking probability during busy hours. The actual number of blockings will be shown later. Although service performance was undesirable, the demand was still great. A high-capacity system for mobile telephones was needed.

Inefficient frequency spectrum utilization. In a conventional mobile telephone system, the frequency utilization measurement M_0 is defined as the maximum number of customers that could be served by one channel at the busy hour. Equation (1.1-1) gives the 1976 New York City data cited earlier.

$$M_0 = \frac{\text{no. of customers}}{\text{channel}} \qquad \text{(conventional systems)} \qquad (1.1\text{-}1)$$

or

$$M_0 = \begin{cases} 53 \text{ customers/channel} & \text{(MJ system)} \\ 37 \text{ customers/channel} & \text{(MK system)} \end{cases}$$

Assume an average calling time of 1.76 min and apply the Erlang B model (lost-calls-cleared conditions). Calculate the blocking probability as follows: Use 6 channels, with each channel serving the two different numbers of customers shown in Eq. (1.1-1). The offered load can then be obtained by Eq. (1.1-2).

$$A = \frac{\text{av calling time (minutes)} \times \text{total customers}}{60 \text{ min}} \quad \text{erlangs} \qquad (1.1\text{-}2)$$

$$A_1 = \frac{1.76 \times 53 \times 6}{60} = 9.33 \text{ erlangs} \qquad \text{(MJ system)}$$

$$A_2 = \frac{1.76 \times 37 \times 6}{60} = 6.51 \text{ erlangs} \qquad \text{(MK system)}$$

Given that the number of channels is 6 and the offered loads are $A_1 = 9.33$ and $A_2 = 6.51$, read from the table in Appendix 1.1 to obtain the blocking probabilities $B_1 = 50$ percent (MJ system) and $B_2 = 30$ percent (MK system), respectively. It is likely that half the initiating calls will be blocked in the MJ system, a very high blocking probability.

If the actual average calling time is greater than 1.76 min, the blocking probability can be even higher. To reduce the blocking probability, we must decrease the value of the frequency spectrum utilization measurement M_0 as shown in Eq. (1.1-1).

As far as frequency spectrum utilization is concerned, the conventional system does not utilize the spectrum efficiently since each channel can only serve one customer at a time in a whole area. A new cellular system that measures the frequency spectrum utilization differently from Eq. (1.1-1) and proves to be efficient is discussed in Sec. 1.1.2.

1.1.2 Spectrum efficiency considerations

A major problem facing the radio communication industry is the limitation of the available radio frequency spectrum. In setting allocation policy, the Federal Communications Commission (FCC) seeks systems which need minimal bandwidth but provide high usage and consumer satisfaction.

The ideal mobile telephone system would operate within a limited assigned frequency band and would serve an almost unlimited number of users in unlimited areas. Three major approaches to achieve the ideal are

1. Single-sideband (SSB), which divides the allocated frequency band into maximum numbers of channels

2. Cellular, which reuses the allocated frequency band in different geographic locations
3. Spread spectrum or frequency-hopped, which generates many codes over a wide frequency band

In 1971, the cellular approach was shown to be a spectrally efficient system.[1] The comparison of an analog cellular approach with other digital cellular system approaches is given in Chap. 15.

1.1.3 Technology, feasibility, and service affordability

In 1971, the computer industry entered a new era. Microprocessors and minicomputers are now used for controlling many complicated features and functions with less power and size than was previously possible. Large-scale integrated (LSI) circuit technology reduced the size of mobile transceivers so that they easily fit into the standard automobile. These achievements were a few of the requirements for developing advanced mobile phone systems and encouraging engineers to pursue this direction.

Another factor was the price reduction of the mobile telephone unit. LSI technology and mass production contribute to reduced cost so that in the near future an average-income family should be able to afford a mobile telephone unit.

On Jan. 4, 1979, the FCC authorized Illinois Bell Telephone Co. (IBT) to conduct a developmental cellular system in the Chicago area and make a limited commercial offering of its cellular service to the public. In addition, American Radio Telephone Service, Inc., (ARTS) was authorized to operate a cellular system in the Washington, D.C.--Baltimore, Md., area. These first systems showed the technological feasibility and affordability of cellular service.

1.1.4 Why 800 MHz?

The FCC's decision to choose 800 MHz was made because of severe spectrum limitations at lower frequency bands. FM broadcasting services operate in the vicinity of 100 MHz. The television broadcasting service starts at 41 MHz and extends up to 960 MHz.

Air-to-ground systems use 118 to 136 MHz; military aircraft use 225 to 400 MHz. The maritime mobile service is located in the vicinity of 160 MHz. Also fixed-station services are allocated portions of the 30- to 100-MHz band. Therefore, it was hard for the FCC to allocate a spectrum in the lower portions of the 30- to 400-MHz band since the services of this band had become so crowded. On the other hand, mobile radio transmission cannot be applied at 10 GHz or above because severe propagation path loss, multipath fading, and rain activity make the medium improper for mobile communications.

Fortunately, 800 MHz was originally assigned to educational TV channels. Cable TV service became a big factor in the mid-70s and shared the load of providing TV channels. This situation opened up the 800-MHz band to some extent, and the FCC allocated a 40-MHz system at 800 MHz to mobile radio cellular systems.

Although 800 MHz is not the ideal transmission medium for mobile radio, it has been demonstrated that a cellular mobile radio system[2,3] that does not go beyond this frequency band can be deployed. Needless to say, the medium of transmitting an 800-MHz signal, although it is workable, is already very difficult. Section 1.6.1 briefly describes the transmission medium.

1.2 History of 800-MHz Spectrum Allocation

In 1958, the Bell System (FCC Docket 11997) proposed a 75-MHz system at 800 MHz, quite a broadband proposal. In 1970, the FCC (Docket 18262)[13] tentatively decided to allocate 75 MHz for a wire-line common carrier. In December 1971 the Bell System assured technical feasibility by showing how a cellular mobile system could be designed.[1] In 1974, the FCC allocated 40 MHz of the spectrum, with one cellular system to be licensed per market. There was considerable uncertainty in predicting the cellular market. However, the FCC strategically placed spectrum reserves totaling 20 MHz in proximity to the cellular allocation.

In 1980, the FCC reconsidered its one-system-per-market strategy and studied the possibility of introducing competition into the previous one-carrier markets. Although cost savings make one cellular system per market attractive, balancing the benefits of economies of scale against the benefits of competition, two licensed carriers per service area was more in line with emerging FCC policies.

Trunking efficiency degradation using two carriers per service area will be discussed in Sec. 1.3. It was the FCC's view that such an approach, while not gaining the full competitive market structure, would provide some competitive advantages. The frequencies will be assigned in 20-MHz groups identified as block A and block B, or called band A and band B.

Two bands serve two different groups in the standard situation: one for wire-line (telephone) companies* and one for non-wire-line (non-

* Let telephone companies operate mobile radio telephone systems.

TABLE 1.1 Mobile and Base Transmission Frequencies*

Band†	Mobile	Base	Two systems/market
A	824–835, 845–846.5	869–880, 890–891.5	Non-wire-line‡
B	835–845, 846.5–849	880–890, 891.5–894	Wire-line

*On July 24, 1986, an additional 5 MHz was allocated to each band. Therefore, an additional 83 channels were added to each band. The system accommodating an additional 83 channels may be ready in mid-1988.

†416 channels per band, 30 kHz per channel.

‡Majority are non-wire-line companies.

telephone) companies. Each company designs its own system and divides the area into geographic areas, or cells. Each cell operates within its own bands (see Table 1.1).

Since 30 kHz is the specified bandwidth, each band operating nowadays consists of 333 channels.† How to utilize these limited resources to provide adequate voice quality and service performance to an unrestricted population size presents a challenge.

1.3 Trunking Efficiency

To explore the trunking efficiency degradation inherent in licensing two or more carriers rather than one, compare the trunking efficiency between one cellular system per market operating 666 channels and two cellular systems per market each operating 333 channels. Assume that all frequency channels are evenly divided into seven subareas called *cells*. In each cell, the blocking probability of 0.02 is assumed. Also the average calling time is assumed to be 1.76 min.

Look up the table of Appendix 1.1 with $N_1 = 666/7 = 95$ and $B = 0.02$ to obtain the offered load $A_1 = 83.1$ and with $N_2 = 333/7 = 47.5$ and $B = 0.02$ to obtain $A_2 = 38$. Since two carriers each operating 333 channels are considered, the total offered load is $2A_2$. We then realize that

$$A_1 \geq 2A_2 \tag{1.3-1}$$

By converting Eq. (1.3-1) to the number of users who can be served in a busy hour, the average calling time of 1.76 min is introduced. The number of calls per hour served in a cell can be expressed as

$$Q_i = \frac{A \times 60}{1.76} \text{ calls/h} \tag{1.3-2}$$

Then

† Most analyses in this book are based on the present channel numbers of 333 channels per system.

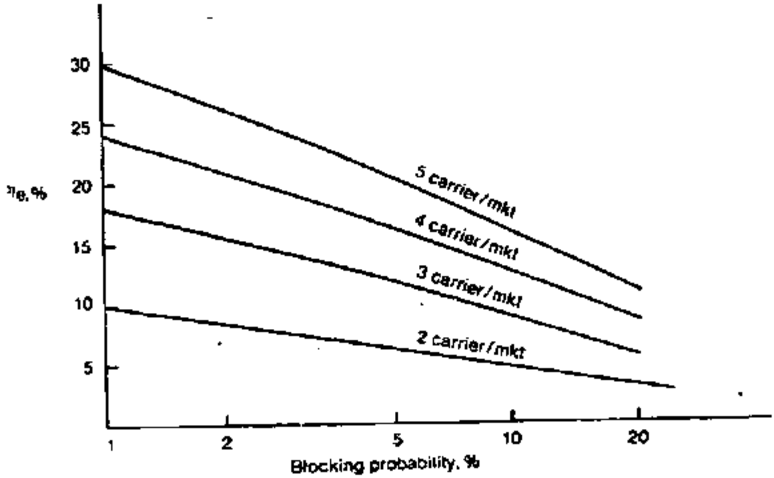


Figure 1.2 Degradation of trunking efficiency—comparing one carrier/market and other-than-one-carrier/market.

$$Q_i = \begin{cases} 2832.95 \text{ calls/h} & \text{(1 carrier/market)} \\ 1295.45 \times 2 = 2590.9 \text{ calls/h} & \text{(2 carriers/market)} \end{cases}$$

The trunking efficiency degradation factor can be calculated as

$$\eta_e = \frac{2832.95 - 2590.9}{2832.95} = 8.5\% \qquad (1.3\text{-}3)$$

for a blocking probability of 2 percent. Figure 1.2 shows η_e by comparing one carrier per market with more than one carrier per market situations with different blocking probability conditions. The degradation of trunking efficiency decreases as the blocking probability increases. As the number of carriers per market increases the degradation increases. However, when a high percentage of blocking probability, say more than 20 percent, occurs, the performance of one carrier per market is already so poor that further degradation becomes insignificant, as Fig. 1.2 shows.

For a 2 percent blocking probability, the trunking efficiency of one carrier per market does show a greater advantage when compared to other scenarios.

1.4 A Basic Cellular System

A basic cellular system consists of three parts: a mobile unit, a cell site, and a mobile telephone switching office (MTSO), as Fig. 1.3 shows, with connections to link the three subsystems.

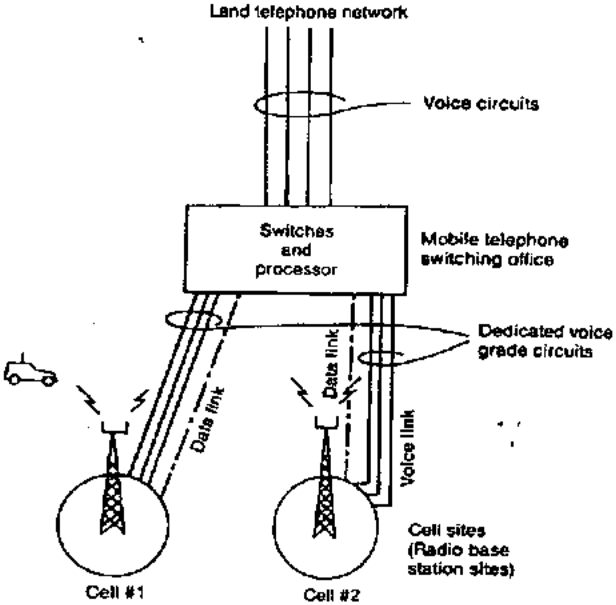


Figure 1.3 Cellular system.

1. *Mobile units.* A mobile telephone unit contains a control unit, a transceiver, and an antenna system.

2. *Cell site.* The cell site provides interface between the MTSO and the mobile units. It has a control unit, radio cabinets, antennas, a power plant, and data terminals.

3. *MTSO.* The switching office, the central coordinating element for all cell sites, contains the cellular processor and cellular switch. It interfaces with telephone company zone offices, controls call processing, and handles billing activities.

4. *Connections.* The radio and high-speed data links connect the three subsystems. Each mobile unit can only use one channel at a time for its communication link. But the channel is not fixed; it can be any one in the entire band assigned by the serving area, with each site having multichannel capabilities that can connect simultaneously to many mobile units.

The MTSO is the heart of the cellular mobile system. Its processor provides central coordination and cellular administration.

The cellular switch, which can be either analog or digital, switches calls to connect mobile subscribers to other mobile subscribers and to the nationwide telephone network. It uses voice trunks similar to telephone company interoffice voice trunks. It also contains data links providing supervision links between the processor and the switch and between the cell sites and the processor. The radio link carries the voice and signaling between the mobile unit and the cell site. The high-speed data links cannot be transmitted over the standard telephone trunks and therefore must use either microwave links or T-carriers (wire lines). Microwave radio links or T-carriers carry both voice and data between the cell site and the MTSO.

1.5 Performance Criteria

There are three categories for specifying performance criteria.

1.5.1 Voice quality

Voice quality is very hard to judge without subjective tests from users' opinions. In this technical area engineers cannot decide how to build a system without knowing the voice quality that will satisfy the users. In military communications, the situation differs: armed forces personnel *must* use the assigned equipment.

For any given commercial communications system, the voice quality will be based upon the following criterion: a set value x at which y percent of customers rate the system voice quality (from transmitter to receiver) as good or excellent, the top two circuit merits (CM) of the five listed below.

CM	Score	Quality scale
CM5	5	Excellent (speech perfectly understandable)
CM4	4	Good (speech easily understandable, some noise)
CM3	3	Fair (speech understandable with a slight effort, occasional repetitions needed)
CM2	2	Poor (speech understandable only with considerable effort, frequent repetitions needed)
CM1	1	Unsatisfactory (speech not understandable)

As the percentage of customers choosing CM4 and CM5 increases, the cost of building the system rises.

The average of the CM scores obtained from all the listeners is called *mean opinion score* (MOS). Usually the toll-quality voice is around MOS ≥ 4.

1.5.2 Service quality

Three items are required for service quality.

1. *Coverage.* The system should serve an area as large as possible. With radio coverage, however, because of irregular terrain configurations, it is usually not practical to cover 100 percent of the area for two reasons:
   a. The transmitted power would have to be very high to illuminate weak spots with sufficient reception, a significant added cost factor.
   b. The higher the transmitted power, the harder it becomes to control interference.

   Therefore, systems usually try to cover 90 percent of an area in flat terrain and 75 percent of an area in hilly terrain. The combined voice quality and coverage criteria in AMPS cellular systems[3] state that 75 percent of users rate the voice quality between good and excellent in 90 percent of the served area, which is generally flat terrain. The voice quality and coverage criteria would be adjusted as per decided various terrain conditions. In hilly terrain, 90 percent of users must rate voice quality good or excellent in 75 percent of the served area. A system operator can lower the percentage values stated above for a low-performance and low-cost system.
2. *Required grade of service.* For a normal start-up system the grade of service is specified for a blocking probability of .02 for initiating calls at the busy hour. This is an average value. However, the blocking probability at each cell site will be different. At the busy hour, near freeways, automobile traffic is usually heavy, so the blocking probability at certain cell sites may be higher than 2 percent, especially when car accidents occur. To decrease the blocking probability requires a good system plan and a sufficient number of radio channels.
3. *Number of dropped calls.* During Q calls in an hour, if a call is dropped and Q − 1 calls are completed, then the call drop rate is 1/Q. This drop rate must be kept low. A high drop rate could be caused by either coverage problems or handoff problems related to inadequate channel availability. How to estimate the number of dropped calls will be described in Chap. 9.

1.5.3 Special features

A system would like to provide as many special features as possible, such as call forwarding, call waiting, voice stored (VSR) box, automatic roaming, or navigation services. However, sometimes the customers may not be willing to pay extra charges for these special services.

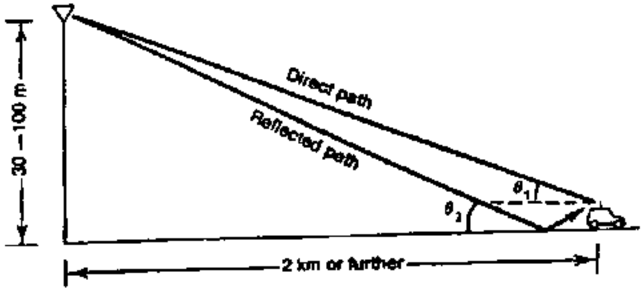


Figure 1.4 Mobile radio transmission model.

1.6 Uniqueness of Mobile Radio Environment

1.6.1 Description of mobile radio transmission medium

The propagation attenuation. In general, the propagation path loss increases not only with frequency but also with distance. If the antenna height at the cell site is 30 to 100 m and at the mobile unit about 3 m, and the distance between the cell site and the mobile unit is usually 2 km or more, then the incident angles of both the direct wave and the reflected wave are very small, as Fig. 1.4 shows. The incident angle of the direct wave is θ_1, and the incident angle of the reflected wave is θ_2. θ_1 is also called the *elevation angle*. The propagation path loss would be 40 dB/dec,[4] where "dec" is an abbreviation of *decade*, i.e., a period of 10. This means that a 40-dB loss at a signal receiver will be observed by the mobile unit as it moves from 1 to 10 km. Therefore C is inversely proportional to R^4.

$$C \propto R^{-4} = \alpha R^{-4} \tag{1.6-1}$$

where C = received carrier power
R = distance measured from the transmitter to the receiver
α = constant

The difference in power reception at two different distances R_1 and R_2 will result in

$$\frac{C_2}{C_1} = \left(\frac{R_2}{R_1}\right)^{-4} \tag{1.6-2a}$$

and the decibel expression of Eq. (1.6-2) is

$$\Delta C \text{ (in dB)} = C_2 - C_1 \text{ (in dB)}$$

$$= 10 \log \frac{C_2}{C_1} = 40 \log \frac{R_1}{R_2} \qquad (1.6\text{-}2b)$$

When $R_2 = 2R_1$, $\Delta C = -12$ dB; when $R_2 = 10R_1$, $\Delta C = -40$ dB.

This 40 dB/dec is the general rule for the mobile radio environment and is easy to remember. It is also easy to compare to the free-space propagation rule of 20 dB/dec. The linear and decibel scale expressions are

$$C \propto R^{-2} \qquad \text{(free space)} \qquad (1.6\text{-}3a)$$

and

$$\Delta C = C_2 \text{ (in dB)} - C_1 \text{ (in dB)}$$

$$= 20 \log \frac{R_1}{R_2} \qquad \text{(free space)} \qquad (1.6\text{-}3b)$$

In a real mobile radio environment, the propagation path-loss slope varies as

$$C \propto R^{-\gamma} = \alpha R^{-\gamma} \qquad (1.6\text{-}4)$$

γ usually lies between 2 and 5 depending on the actual conditions.[5] Of course γ cannot be lower than 2, which is the free-space condition. The decibel scale expression of Eq. (1.6-4) is

$$C = 10 \log \alpha - 10\gamma \log R \qquad \text{dB} \qquad (1.6\text{-}5)$$

Severe fading. Since the antenna height of the mobile unit is lower than its typical surroundings, and the carrier frequency wavelength is much less than the sizes of the surrounding structures, multipath waves are generated. At the mobile unit, the sum of the multipath waves causes a signal-fading phenomenon. The signal fluctuates in a range of about 40 dB (10 dB above and 30 dB below the average signal). We can visualize the nulls of the fluctuation at the baseband at about every half wavelength in space, but all nulls do not occur at the same level, as Fig. 1.5 shows. If the mobile unit moves fast, the rate of fluctuation is fast. For instance, at 850 MHz, the wavelength is roughly 0.35 m (1 ft). If the speed of the mobile unit is 24 km/h (15 mi/h), or 6.7 m/s, the rate of fluctuation of the signal reception at a 10-dB level below the average power of a fading signal is 15 nulls per second (see Sec. 1.6.3).

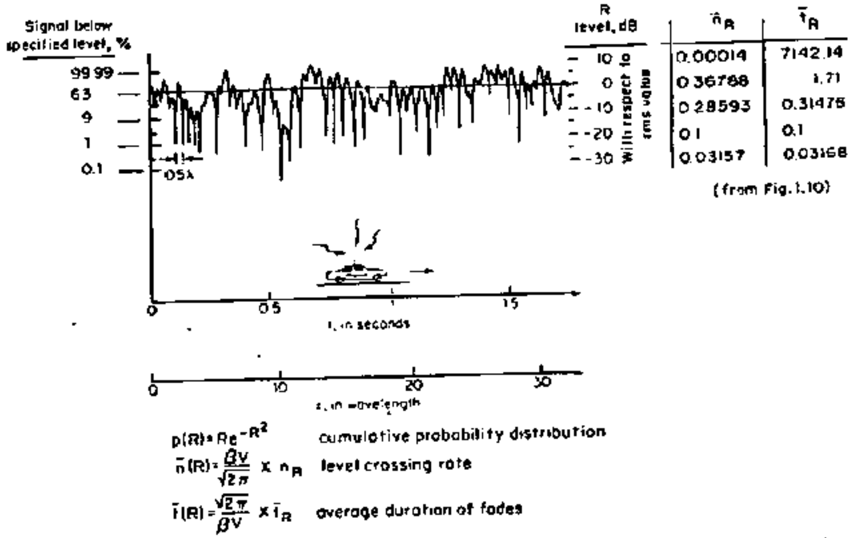


Figure 1.5 A typical fading signal received while the mobile unit is moving. *(Reprint after Lee, Ref. 4, p. 46.)*

1.6.2 Model of transmission medium

A mobile radio signal $r(t)$, illustrated in Fig. 1.6, can be artificially characterized by two components $m(t)$ and $r_0(t)$ based on natural physical phenomena.

$$r(t) = m(t)r_0(t) \tag{1.6-6}$$

The component $m(t)$ is called *local mean, long-term fading,* or *lognormal fading* and its variation is due to the terrain contour between the base station and the mobile unit. The factor r_0 is called *multipath fading, short-term fading,* or *Rayleigh fading* and its variation is due to the waves reflected from the surrounding buildings and other structures. The long-term fading $m(t)$ can be obtained from Eq. (1.6-7*a*).

$$m(t_1) = \frac{1}{2T}\int_{t_1-T}^{t_1+T} r(t)\,dt \tag{1.6-7a}$$

where $2T$ is the time interval for averaging $r(t)$. T can be determined based on the fading rate of $r(t)$, usually 40 to 80 fades.[5] Therefore, $m(t)$ is the envelope of $r(t)$, as shown in Fig. 1.6*a*. Equation (1.6-7*a*) also can be expressed in spatial scale as

$$m(x_1) = \frac{1}{2L}\int_{x_1-L}^{x_1+L} r(x)\,dx \tag{1.6-7b}$$

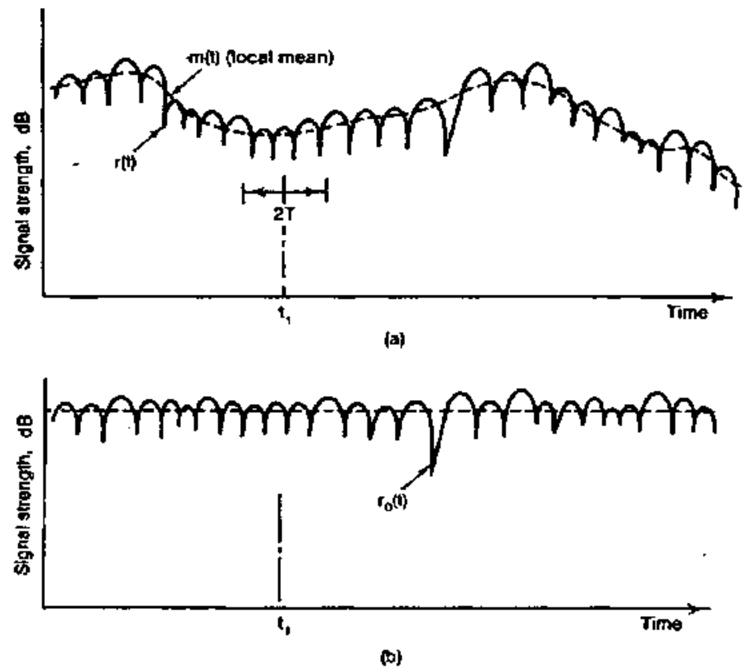


Figure 1.6 A mobile radio signal fading representation. (*a*) A mobile signal fading. (*b*) A short-term signal fading.

The length of $2L$ has been determined to be 20 to 40 wavelengths.[5] Using 36 or up to 50 samples in an interval of 40 wavelengths is an adequate averaging process for obtaining the local means.[4]

The factor $m(t)$ or $m(x)$ is also found to be a log-normal distribution based on its characteristics caused by the terrain contour. The short-term fading r_0 is obtained by

$$r_0 \text{ (in dB)} = r(t) - m(t) \qquad \text{dB} \tag{1.6-8}$$

as shown in Fig. 1.6b. The factor $r_0(t)$ follows a Rayleigh distribution, assuming that only reflected waves from local surroundings are the ones received (a normal situation for the mobile radio environment). Therefore, the term Rayleigh fading is often used.

1.6.3 Mobile fading characteristics

Rayleigh fading is also called multipath fading in the mobile radio environment. When these multipath waves bounce back and forth due to the buildings and houses, they form many standing-wave pairs in

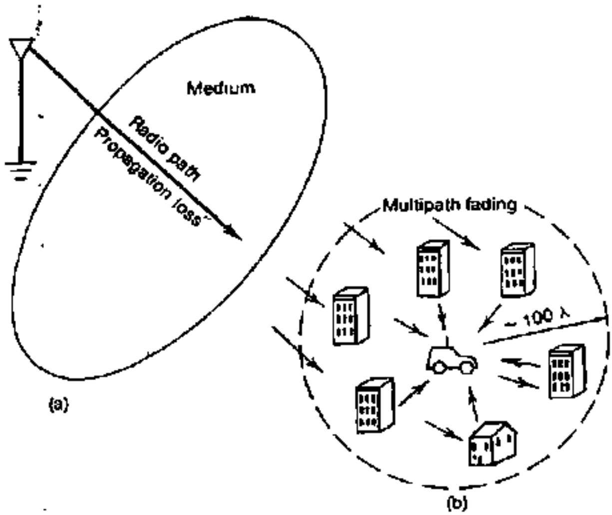


Figure 1.7 A mobile radio environment—two parts. (1) Propagation loss; (2) multipath fading.

space, as shown in Fig. 1.7. Those standing-wave pairs are summed together and become an irregular wave-fading structure. When a mobile unit is standing still, its receiver only receives a signal strength at that spot, so a constant signal is observed. When the mobile unit is moving, the fading structure of the wave in the space is received. It is a multipath fading. The recorded fading becomes fast as the vehicle moves faster.

The radius of the active scatterer region. The mobile radio multipath fading shown in Fig. 1.7 explains the fading mechanism. The radius of the active scatterer region at 850 MHz can be obtained indirectly as shown in Ref. 12. The radius is roughly 100 wavelengths. The active scatterer region always moves with the mobile unit as its center. It means that some houses were inactive scatterers and became active as the mobile unit approached them; some houses were active scatterers and became inactive as the mobile unit drove away from them.

Standing waves expressed in a linear scale and a log scale. We first introduce a sine wave in a log scale.

$$y = 10 \cos \beta x \qquad \text{dB} \tag{1.6-9}$$

A log plot of the sine wave of Eq. (1.6-9) is shown in Fig. 1.8*a*. The linear expression of Eq. (1.6-9) then is shown in Fig. 1.8*b*. The sym-

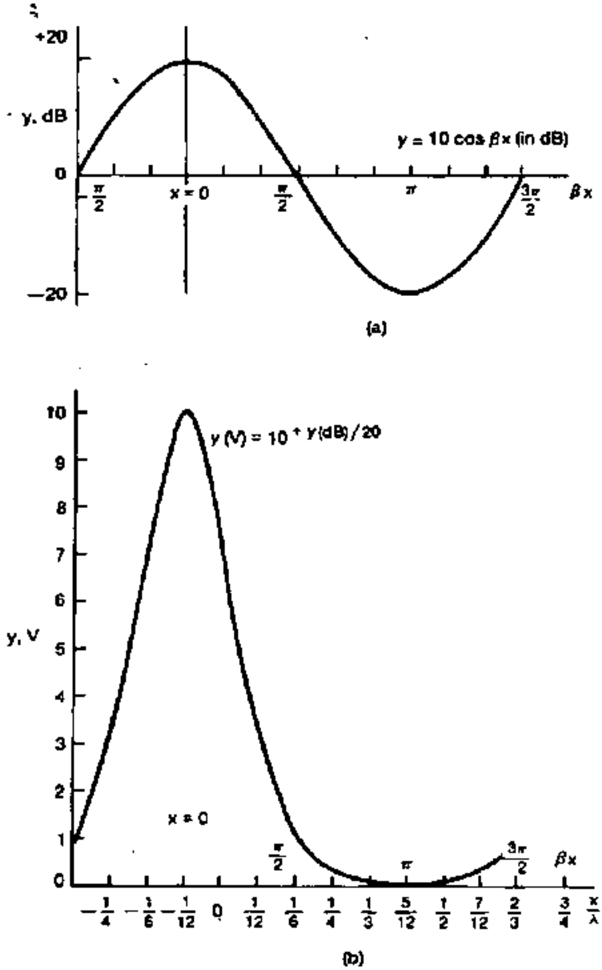


Figure 1.8 The linear plot and the log plot of a sine wave. (*a*) In linear scale; (*b*) in log scale.

metrical waveform in a log plot becomes an unsymmetrical waveform when plotted on a linear scale. It shows that the sine wave waveform in a log scale becomes a completely different waveform when expressed on a linear scale and vice versa. Two sine waves, the incident wave traveling along the x-axis (traveling to the left) and the reflected wave traveling in the opposite direction, can be expressed as

$$e_0 = E_0 e^{j(\omega t + \beta x)} \tag{1.6-10}$$

and
$$e_1 = E_1 e^{j(\omega t - \beta x + \delta)} \tag{1.6-11}$$

where ω = angular frequency
β = wave number ($= 2\pi/\lambda$)
δ = time-phase lead of e_1 with respect to e_0 at $x = 0$

The two waves form a standing-wave pattern.

$$e = e_0 + e_1 = R \cos(\omega t - \delta) \tag{1.6-12}$$

where the amplitude R becomes

$$R = \sqrt{(E_0 + E_1)^2 \cos^2 \beta x + (E_0 - E_1)^2 \sin^2 \beta x} \tag{1.6-13}$$

We are plotting two cases.

Case 1. $E_0 = 1$, $E_1 = 1$; that is, the reflection coefficient = 1,

$$\text{Standing wave ratio (SWR)} = \frac{E_0 + E_1}{E_0 - E_1} = \infty$$

and
$$R = 2 \cos \beta x \tag{1.6-14}$$

Case 2. $E_0 = 1$, $E_1 = 0.5$; that is, the reflection coefficient = 0.5, SWR = 3, and

$$R = \sqrt{(1.5)^2 \cos^2 \beta x + (0.5)^2 \sin^2 \beta x} \tag{1.6-15}$$

The linear expression of Eqs. (1.6-14) and (1.6-15) are shown in Fig. 1.9*a*. The log-scale expression of Eqs. (1.6-14) and (1.6-15) are shown in Fig. 1.9*b*. The waveform of Fig. 1.9*b* is the first sign of the fading signal which resembles the real fading signal shown in Fig. 1.5.

First-order and second-order statistics of fading. Fading occurs on the signal reception when the mobile unit is moving. The first-order statistics, such as average power probability cumulative distribution function (CDF) and bit error rate, are independent of time. The second-order statistics, such as level crossing rate, average duration of fades, and word error rate, are time functions or velocity-related functions. The data signaling format is based on these characteristics. The description of the fading characteristic can be found in detail in two books, Refs. 4 and 5.

Some data can be found from Fig. 1.10*a*, the cumulative distribution function (CDF), and Fig. 1.10*b*, the level crossing rate. In Fig. 1.10*a*, the equation of CDF for a Rayleigh fading is used as follows:

$$P(x \le A) = 1 - e^{-A^2/\bar{A}^2} \tag{1.6-16}$$

and
$$P(y \le L) = 1 - e^{-L/\bar{L}} \tag{1.6-17}$$

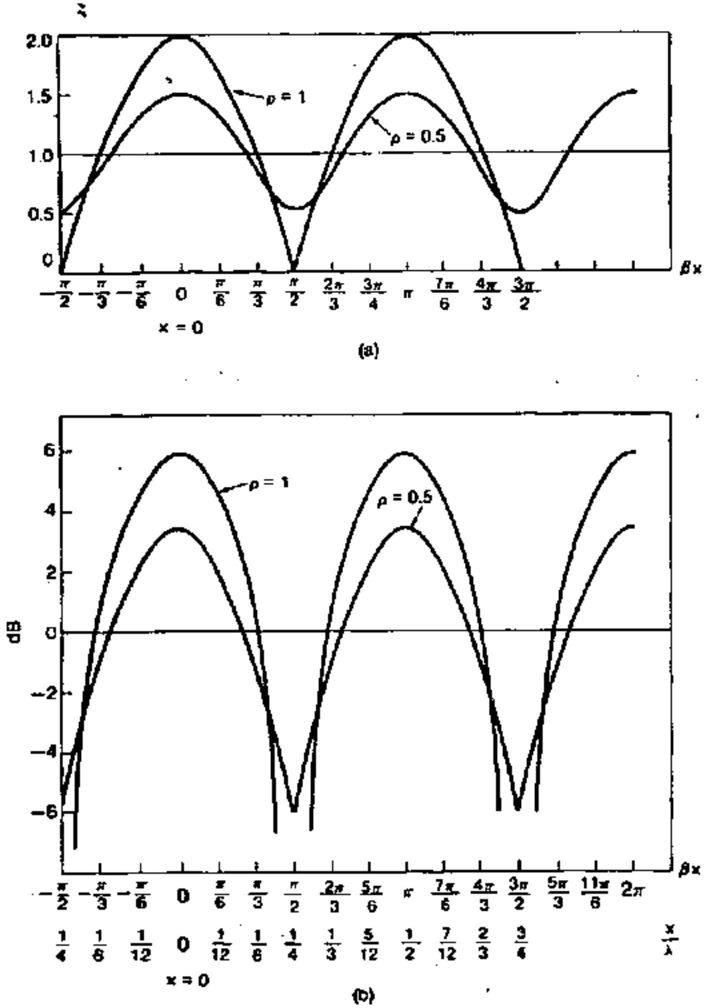
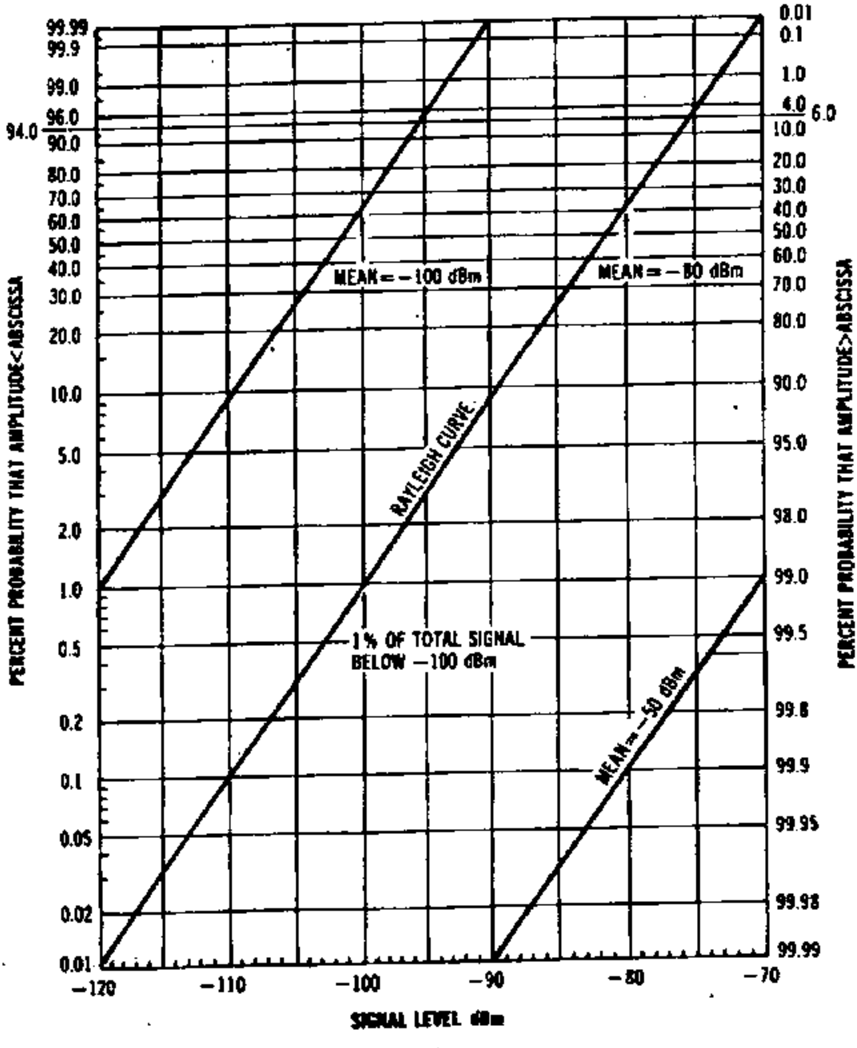


Figure 1.9 The linear plot and the log plot of a standing wave. (*a*) In linear scale; (*b*) in log scale.

where $\overline{A^2}$ and $\overline{L}$ are the mean square value and the average power, respectively. In Fig. 1.10*a*, about 9 percent of the total signal is below a level of −10 dB with respect to average power. In Fig. 1.10*b*, the level crossing rate (lcr) at a level A is

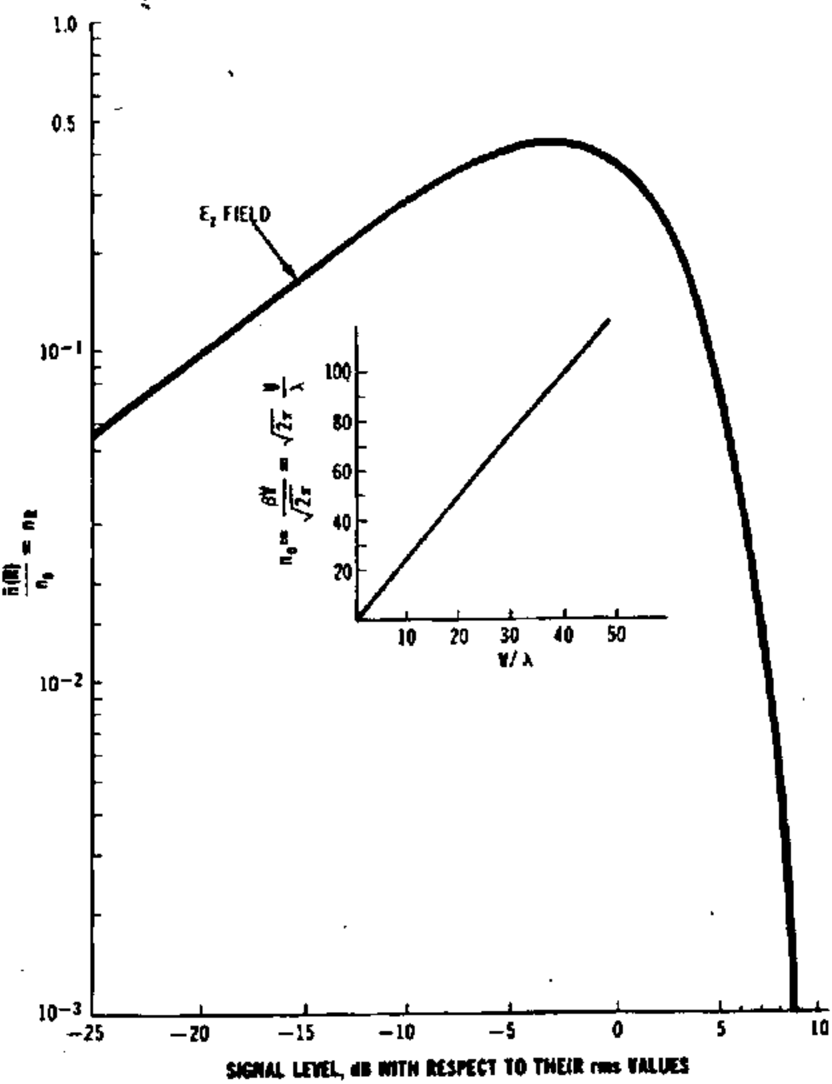
$$\overline{n}(A) = \frac{\beta v}{\sqrt{2\pi}}\, n_R$$



(a)

Figure 1.10 Fading characteristics. (*a*) CDF. *(After Lee, Ref. 5, p. 33.)* (*b*) Level crossing rate. (*c*) Average duration of fades.

where n_R is the normalized lcr which is independent of wavelength and the car speed. At a level of −10 dB, n_0 = 0.3 can be found from Fig. 1.10*b*. Assume that a signal of 850 MHz is received at a mobile unit with a velocity of 24 km/h (15 mi/h). Then



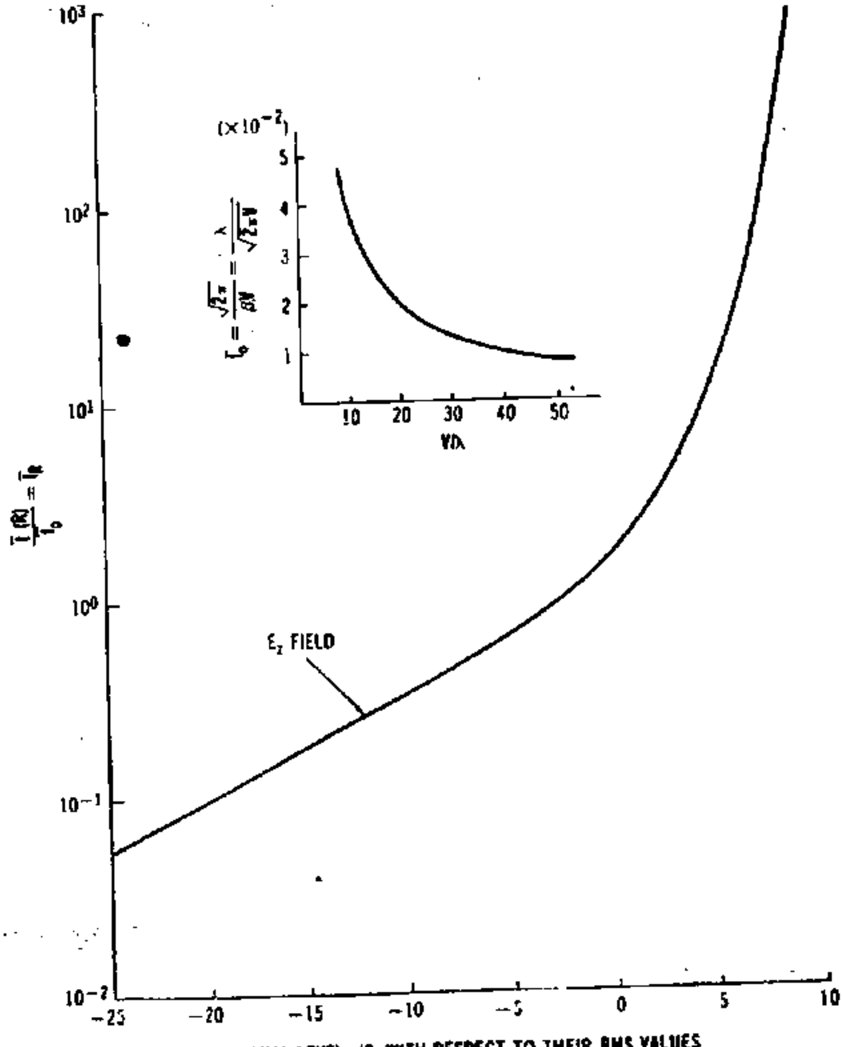
(b)

Figure 1.10 *(Continued)*

$$n_0 = \frac{\beta V}{\sqrt{2\pi}} \approx 50$$

and

$$\overline{n} = 50 \times 0.3 = 15$$



(c)

Figure 1.10 *(Continued)*

Therefore, at a cellular frequency of 800 MHz and a vehicle velocity of 15 mi/h, the level crossing rate is 15 per second. It is easy to remember.

The average duration of fade is

$$\bar{t} = \frac{\text{CDF}}{\bar{t}_0 \bar{t}_R} = \frac{\text{CDF}}{\bar{n}} \tag{1.6-19}$$

Equation (1.6-19) is plotted in Fig. 1.10*c*, where t_0 and t_R are also shown. At -10 dB, the average duration of fades is

$$\bar{t} = \frac{\text{CDF}}{\bar{n}} = 0.0066 \text{ s} = 6.6 \text{ ms}$$

Now the average power level plays an important role in determining the statistics. Therefore, it should be specified by the system design. The second-order statistic of fading phenomenon is most useful for designing a signaling format for the cellular system. As soon as the signaling format is specified, we can calculate the bit error rate and the word error rate and find ways to reduce the error rates, which will be described in Sec. 13.2.

Delay spread and coherence bandwidth

Delay spread. In the mobile radio environment, as a result of the multipath reflection phenomenon, the signal transmitted from a cell site and arriving at a mobile unit will be from different paths, and since each path has a different path length, the time of arrival for each path is different. For an impulse transmitted at the cell site, by the time this impulse is received at the mobile unit it is no longer an impulse but rather a pulse with a spread width that we call the *delay spread.* The measured data indicate that the mean delay spreads are different in different kinds of environment.

Type of environment	Delay spread Δ, μs
Inside the building	<0.1
Open area	<0.2
Suburban area	0.5
Urban area	3

Coherence bandwidth. The coherence bandwidth is the defined bandwidth in which either the amplitudes or the phases of two received signals have a high degree of similarity. The delay spread is a natural phenomenon, and the coherence bandwidth is a defined creation related to the delay spread.

A coherence bandwidth for two fading amplitudes of two received signals is

$$B_c = \frac{1}{2\pi\Delta}$$

A coherence bandwidth for two random phases of two received signals is

$$B'_c = \frac{1}{4\pi\Delta}$$

1.6.4 Direct wave path, line-of-sight path, and obstructive path

A *direct wave path* is a path clear from the terrain contour. The *line-of-sight path* is a path clear from buildings. In the mobile radio environment, we do not always have a line-of-sight condition.

When a line-of-sight condition occurs, the average received signal at the mobile unit at a 1-mi intercept is higher, although the 40 dB/dec path-loss slope remains the same. It will be described in Sec. 4.2. In this case the short-term fading is observed to be a rician fading.[14] It results from a strong line-of-sight path and a ground-reflected wave combined, plus many weak building-reflected waves.

When an out-of-sight condition is reached, the 40-dB/dec path-loss slope still remains. However, all reflected waves, including ground reflected waves and building-reflected waves, become dominant. The short-term received signal at the mobile unit observes a Rayleigh fading. The Rayleigh fading is the most severe fading.

When the terrain contour blocks the direct wave path, we call it the *obstructive path*. In this situation, the shadow loss from the signal reception can be found by using the knife-edge diffraction curves shown in Sec. 4.7.2.

1.6.5 Noise level in cellular frequency band

The thermal noise kTB at a temperature T of 290 K (17°C) and a bandwidth B of 30 kHz is -129 dBm.* Assume that the received front-end noise is 9 dB, then the noise level is -120 dBm. Now there are two kinds of man-made noise, the ignition noise generated by the vehicles and the noise generated by 800-MHz emissions.

* k is Boltzmann's constant, and $kT = -174$ dBm/Hz at $T = 290$ K.

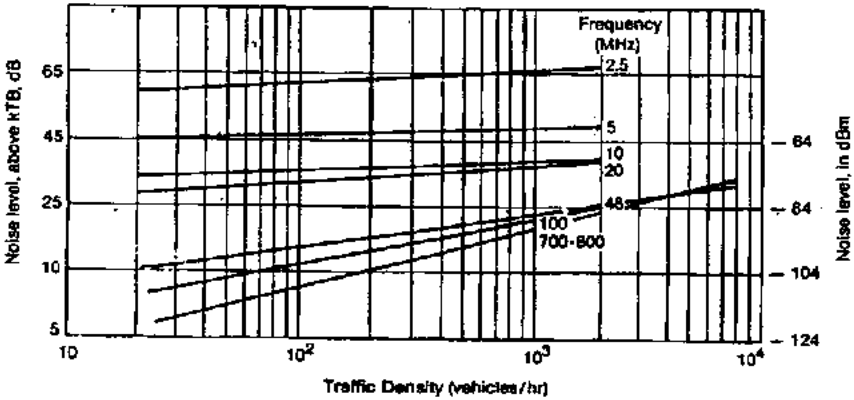


Figure 1.11 Average automotive-traffic-noise power for various traffic densities and frequencies. Detector noise bandwidth 30 kHz at room temperature (17°C). *(After Lee, Ref. 16.)*

The ignition noise. In the past, 800 MHz was not widely used. Therefore, the man-made noise at 800 MHz is merely generated by the vehicle ignition noise.[10] The automotive noise introduced at 800 MHz with a bandwidth of 30 kHz can be deduced from Ref. 15, as shown in Fig. 1.11.

The 800-MHz-emission noise. As a result of the cellular mobile systems operating in all the major cities in the United States and the spurious energy generated outside each channel bandwidth, the early noise data measurements[9,10] are no longer valid. The 800-MHz-emission noise can be measured at an idle channel (a forward voice channel) in the 869- to 894-MHz region while the mobile receiver is operating on a car battery in a no-traffic spot in a city. In this case, no automotive ignition noise is involved, and no cochannel operation is in the proximity of the idle-channel receiver. We found that in some areas the noise level is 2 to 3 dB higher than −120 dBm at the cell sites and 3 to 4 dB higher than −120 dBm at the mobile stations.

1.6.6 Amplifier noise

A mobile radio signal received by a receiving antenna, either at the cell site or at the mobile unit, will be amplified by an amplifier. We would like to understand how the signal is affected by the amplifier noise. Assume that the amplifier has an available power gain g and the available noise power at the output is N_0. The input signal-to-noise

(S/N) ratio is P_s/N_i, the output signal-to-noise ratio is P_o/N_o, and the internal amplifier noise is N_a. Then the output P_o/N_o becomes

$$\frac{P_o}{N_o} = \frac{gP_s}{g(N_i) + N_a} = \frac{P_s}{N_i + (N_a/g)} \tag{1.6-20}$$

The noise figure F is defined as

$$F = \frac{\text{maximum possible S/N ratio}}{\text{actual S/N ratio at output}} \tag{1.6-21}$$

where the maximum possible S/N ratio is measured when the load is an open circuit. Equation (1.6-21) can be used for obtaining the noise figure of the amplifier.

$$F = \frac{P_s/kTB}{P_o/N_o} = \frac{N_o}{(P_o/P_s)kTB} = \frac{N_o}{g(kTB)} \tag{1.6-22}$$

Also substituting Eq. (1.6-20) into Eq. (1.6-22) yields

$$F = \frac{P_s/kTB}{P_s/[N_i + (N_a/g)]} = \frac{N_i + (N_a/g)}{kTB} \tag{1.6-23}$$

The term kTB is the thermal noise as described in Sec. 1.6.5. The noise figure is a reference measurement between a minimum noise level due to thermal noise and the noise level generated by both the external and internal noise of an amplifier.

1.7 Operation of Cellular Systems

This section briefly describes the operation of the cellular mobile system from a customer's perception without touching on the design parameters.[17,18] The operation can be divided into four parts and a handoff procedure.

Mobile unit initialization. When a user sitting in a car activates the receiver of the mobile unit, the receiver scans 21 set-up channels which are designated among the 416 channels. It then selects the strongest and locks on for a certain time. Since each site is assigned a different set-up channel, locking onto the strongest set-up channel usually means selecting the nearest cell site. This self-location scheme is used in the idle stage and is user-independent. It has a great advantage because it eliminates the load on the transmission at the cell site for locating the mobile unit. The disadvantage of the self-location scheme is that no location information of idle mobile units appears at each cell site. Therefore, when the call initiates from the land line to a mobile unit, the paging process is longer. Since a large percentage of calls originates at the mobile unit, the use of self-location schemes is justified. After 60 s, the self-location procedure is repeated. In the future, when land-line originated calls increase, a feature called "registration" can be used.

Mobile originated call. The user places the called number into an originating register in the mobile unit, checks to see that the number is correct, and pushes the "send" button. A request for service is sent on a selected set-up channel obtained from a self-location scheme. The cell site receives it, and in directional cell sites, selects the best directive antenna for the voice channel to use. At the same time the cell site sends a request to the mobile telephone switching office (MTSO) via a high-speed data link. The MTSO selects an appropriate voice channel for the call, and the cell site acts on it through the best directive antenna to link the mobile unit. The MTSO also connects the wire-line party through the telephone company zone office.

Network originated call. A land-line party dials a mobile unit number. The telephone company zone office recognizes that the number is mobile and forwards the call to the MTSO. The MTSO sends a paging message to certain cell sites based on the mobile unit number and the search algorithm. Each cell site transmits the page on its own set-up channel. The mobile unit recognizes its own identification on a strong set-up channel, locks onto it, and responds to the cell site. The mobile unit also follows the instruction to tune to an assigned voice channel and initiate user alert.

Call termination. When the mobile user turns off the transmitter, a particular signal (signaling tone) transmits to the cell site, and both sides free the voice channel. The mobile unit resumes monitoring pages through the strongest set-up channel.

Handoff procedure. During the call, two parties are on a voice channel. When the mobile unit moves out of the coverage area of a particular cell site, the reception becomes weak. The present cell site requests a handoff. The system switches the call to a new frequency channel in a new cell site without either interrupting the call or alerting the user. The call continues as long as the user is talking. The user does not notice the handoff occurrences. *Handoff* was first used by the AMPS system, then renamed *handover* by the European systems because the different meanings in English English and American English. Description of handoff will appear in Chap. 9.

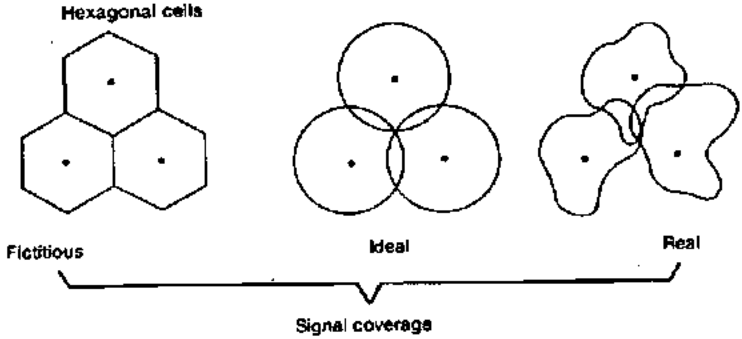


Figure 1.12 Hexagonal cells and the real shapes of their coverages.

1.8 Marketing Image of Hexagonal-shaped Cells

We have to realize that hexagonal-shaped communication cells are artificial and that such a shape cannot be generated in the real world. Engineers draw hexagonal-shaped cells on a layout to simplify the planning and design of a cellular system because it approaches a circular shape that is the ideal power coverage area. The circular shapes have overlapped areas which make the drawing unclear. The hexagonal-shaped cells fit the planned area nicely, as shown in Fig. 1.12, with no gap and no overlap between the hexagonal cells. The ideal cell shapes as well as the real cell shapes are also shown in Fig. 1.12.

A simple mechanism which makes the cellular system implementable based on hexagonal cells will be illustrated in later chapters. Otherwise, a statistical approach will be used in dealing with a real-world situation. Fortunately, the outcomes resulting from these two approaches are very close, yet the latter does not provide a clear physical picture, as shown later. Besides, today these hexagonal-shaped cells have already become a widely promoted symbol for cellular mobile systems. An analysis using hexagonal cells, if it is desired, can easily be adapted by the reader.

1.9 Planning a Cellular System

1.9.1 How to start planning

Assume that the construction permit for a cellular system in a particular market area is granted. The planning stage becomes critical. A great deal of money can be spent and yet poor service may be provided if we do not know how to create a good plan. First, we have to determine two elements: regulations and the market situation.

Regulations. The federal regulations administered by the FCC are the same throughout the United States. The state regulations may be different from state to state, and each city and town may have its own building codes and zoning laws. Become familiar with the rules and regulations. Sometimes waivers need to be applied for ahead of time. Be sure that the plan is workable.

Market situation. There are three tasks to be handled by the marketing department.

1. *Prediction of gross income.* We have to determine the population, average income, business types, and business zones so that the gross income can be predicted.
2. *Understanding competitors.* We also need to know the competitor's situation, coverage, system performance, and number of customers. Any system should provide a unique and outstanding service to overcome the competition.
3. *Decision* of *geographic coverage.* What general area should ultimately be covered? What near-term service can be provided in a limited area? These questions should be answered and the decisions passed on to the engineering department.

1.9.2 The engineer's role

The engineers follow the market decisions by

1. Initiating a cellular mobile service in a given area by creating a plan that uses a minimum number of cell sites to cover the whole area. It is easy for marketing to request but hard for the engineers to fulfill. We will address this topic later.
2. Checking the areas that marketing indicated were important revenue areas. The number of radios (number of voice channels) required to handle the traffic load at the busy hours should be determined.
3. Studying the interference problems, such as cochannel and adjacent channel interference, and the intermodulation products generated at the cell sites, and finding ways to reduce them.
4. Studying the blocking probability of each call at each cell site, and trying to minimize it.
5. Planning to absorb more new customers. The rate at which new customers subscribe to a system can vary depending on the service charges, system performance, and seasons of the year. Engineering has to try to develop new technologies to utilize fully the limited

spectrum assigned to the cellular system. The analysis of spectrum efficiency due to the natural limitations may lead to a request for a larger spectrum.

1.9.3 Finding solutions

Many practical design tools, methods of reducing interference, and ways of solving the blocking probability of call initiation will be introduced in this book.

1.10 Analog Cellular Systems

1.10.1 Cellular systems in the United States

There are 150 major market areas* in the United States where licenses for cellular systems can be granted by the FCC. They have been classified by their populations into five groups. Each group has 30 cities.

1. Top 30 markets—very large cities
2. Top 31 to 60 markets—large-sized cities
3. Top 61 to 90 markets—medium-sized cities
4. Top 91 to 120 markets—below medium-sized cities
5. Top 121 to 150 markets—small-sized cities

Each market area is planned to have two systems. The status of each system in each area of groups 1 to 3 as of December 1985 appears in Appendix 1.2. The specifications of the system are described in detail in Chap. 3. There are 305 MSAs (metropolitan statistical areas) and 482 RSAs (rural statistical areas). Both MSAs and RSAs are listed in Appendix 1.3.

1.10.2 Cellular systems outside the United States

Japan.[8] Nippon Telegraph and Telephone Corporation (NTT) developed an 800-MHz land mobile telephone system and put it into service in the Tokyo area in 1979. The general system operation is similar to the AMPS system. It accesses approximately 40,000 subscribers in 500 cities. It covers 75 percent of all Japanese cities, 25 percent of inhabitable areas, and 60 percent of the population. In Japan, 9 automobile switching centers (ASCs), 51 mobile control stations (MCSs), 465 mo-

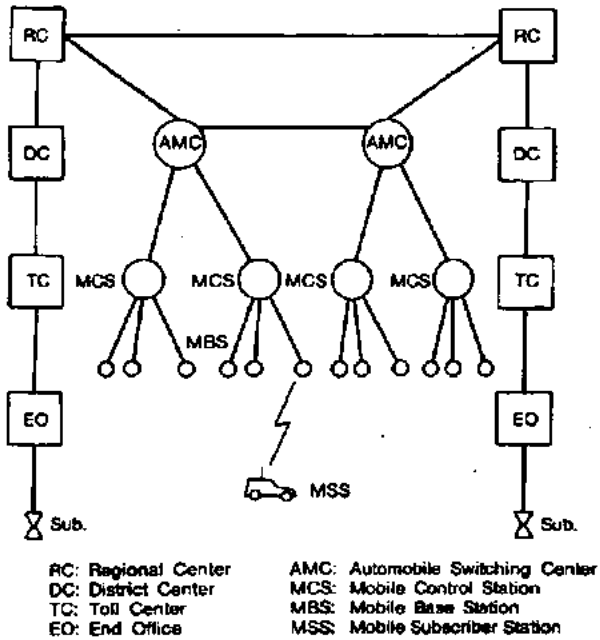


Figure 1.13 Japanese mobile telephone service network configuration.

bile base stations (MBSs), and 39,000 mobile subscriber stations (MSSs) were in operation as of February 1985.

The Japanese mobile telephone service network configuration is shown in Fig. 1.13. In the metropolitan Tokyo area, about 30,000 subscribers are being served.

The 1985 system operated over a spectrum of 30 MHz. The total number of channels was 600, and the channel bandwidth was 25 kHz. This system comprised an automobile switching center (ASC), a mobile control station (MCS), a mobile base station (MBS), and a mobile subscriber station (MSS). At present there is no competitive situation set up by the government. However, the Japanese Ministry of Post and Telecommunication (MFT) is considering providing a dual competitive situation similar to that in the United States.

United Kingdom.[7] In June 1982 the government of the United Kingdom announced two competing national cellular radio networks. The UK system is called TACS (Total Access Communications System). The total number of channels was 1000, with a channel bandwidth of

25 kHz per channel. Among them, 600 channels are assigned and 400 are reserved. Two competing cellular network operators, Cellnet and Vodafone, are operating in the United Kingdom. Each network system has only 300 spectral channels. The Cellnet system started operating in January 1985. Cellnet has over 200 cell sites, covering 82 percent of the United Kingdom. Vodaphone, though, which started operations late, has served the same areas as Cellnet.

Canadian system.[8] In 1978, a system called AURORA was designed for the Alberta government telephone (AGT). The system provides provincewide mobile telephone service at 400 MHz. Ongoing developmental work on the AURORA is underway at 800 MHz.

AURORA 400 system. It is aimed at 40,000 subscribers living in an area approximately 1920 km × 960 km. The AURORA 400 system initially has 40 channels and is expected to add an additional 20 channels with frequency reuse and a seven-cell cluster plan. A fully implemented system has 120 cells. The 400-MHz system does not have a handoff capability.

AURORA 800 system. The AURORA 800 system is truly frequency-transparent. By repackaging the radio frequency (RF) sections on the cell site, the mobile unit can be operated on any mobile RF band up to 800 MHz. The handoff capability will be implemented in this system.

Nordic system. This system was built mostly by Scandinavian countries (Denmark, Norway, Sweden, and Finland) in cooperation with Saudi Arabia and Spain and is called the *NMT network*. It is currently a 450-MHz system, but an 800-MHz system will be implemented soon since the frequency-transparent concept as the AURORA 800 system is used to convert the 450-MHz system to the 800-MHz system.

The total bandwidth is 10 MHz, which has 200 channels with a bandwidth of 25 kHz per channel. This system does have handoff and roaming capabilities. It also uses repeaters to increase the coverage in a low traffic area. The total number of subscribers is around 100,000.

European cellular systems.[11] All the present generation of European cellular networks is totally lacking in cross-border compatibility. Besides the United Kingdom and NMT networks, the others include the following.

Benelux-country network. The Netherlands served on their ATF2 network (the same as the NMT 450 network) at the beginning of 1985. It has a nationwide coverage using 50 cell sites with two different cell sizes, 20- and 5-km radii. The capacity of the present system is 15,000 to 20,000 subscribers. Dutch PT&T is using a single Ericsson AXE10 switch. Luxembourg came on air in August 1985. In 1986, Belgium joined the network. It operates at 450 MHz. The network is compatible among the three countries.

France. A direct-dial car telephone operating at 160 MHz can access the system in 10 regional areas. The network serves 10,000 subscribers. By the end of 1984, 450 MHz was in operation. In the meantime Radicom 2000 (digital signaling) was introduced, operating at 200 MHz but with no handoff feature.

Spain. It uses an NMT 450-MHz cellular network introduced in 1982. It was the first cellular system in Europe. The number of cells in service is 13. There are three separate networks operating 104 channels. Each channel bandwidth is 25 kHz.

Austria. A new NMT cellular network called *Autotelefonnetz C* has two mobile switching exchanges and has enough capacity for 30,000 subscribers.

The Austrian PT&T has allocated 222 duplex channels in ranges 451.3 to 455.7 MHz and 461.3 to 465.7 MHz, with a channel bandwidth of 20 kHz.

Although both Austria and Spain are using NMT 450 systems, their systems are not compatible because of different frequency allocations, channel spacings (bandwidth), and protocols by different PT&Ts.

Germany. A full national coverage, including West Berlin, using a C-450 cellular system was installed in September 1985 with 100 cell sites. Another 75 cell sites were completed in mid-1986. Also, Germany and France are working on cross-border compatibility in cellular radio systems and have proposed a CD-900 digital system. The details of the CD-900 system will be described in Chap. 14.

Switzerland. Swiss PT&T decided to install an NMT 900-MHz cellular network that had a capacity of 12,000 subscribers. A pilot scheme with 20 transmitters (cell sites) was installed in the Zurich area in late 1986.

Cellular systems in the rest of the world. Australia is installing a system using Ericsson's AXE-10 switching network and will operate at 800 MHz with 12 sites concentrated in three big cities.

Kuwait's cellular system uses NEC's switches and provides 12 sites. It operates at 800 MHz.

Hong Kong has three systems. The United Kingdom's TACS system is installed with Motorola switches. The United States' AMPS system and Japanese NEC systems were also installed in Hong Kong. It is a very competitive market. All systems are penetrating the markets of both portable sets and car sets.

1.11 Digital Cellular Systems

In 1992 the first digital cellular system, GSM (Special Mobile Group), was deployed in Germany. GSM is a European standard system. In the United States, an NA-TDMA system (IS-54) and a CDMA system (IS-95) have been developed. NA-TDMA was deployed in 1993 and CDMA is planned for deployment in 1995. A Japanese system, PDC (Personal Digital Cellular), was deployed in Osaka in June 1994. All the digital cellular systems and some noncellular digital systems will be described in Chap. 15.

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Appendix 1.1
Blocked-Calls-Cleared (Erlang *B*)

	A, erlangs												
	B												
N	1.0%	1.2%	1.5%	2%	3%	5%	7%	10%	15%	20%	30%	40%	50%
1	.0101	.0121	.0152	.0204	.0309	.0526	.0753	.111	.176	.250	.429	.667	1.00
2	.153	.168	.190	.223	.282	.381	.470	.595	.796	1.00	1.45	2.00	2.73
3	.455	.489	.535	.602	.715	.899	1.06	1.27	1.60	1.93	2.63	3.48	4.59
4	.869	.922	.992	1.09	1.26	1.52	1.75	2.05	2.50	2.95	3.39	5.02	6.50
5	1.36	1.43	1.52	1.66	1.88	2.22	2.50	2.88	3.45	4.01	5.19	6.60	8.44
6	1.91	2.00	2.11	2.28	2.54	2.96	3.30	3.76	4.44	5.11	6.51	8.19	10.4
7	2.50	2.60	2.74	2.94	3.25	3.74	4.14	4.67	5.46	6.23	7.86	9.80	12.4
8	3.13	3.25	3.40	3.63	3.99	4.54	5.00	5.60	6.50	7.37	9.21	11.4	14.3
9	3.78	3.92	4.09	4.34	4.75	5.37	5.88	6.55	7.55	8.52	10.6	13.0	16.3
10	4.46	4.61	4.81	5.08	5.53	6.22	6.78	7.51	8.62	9.68	12.0	14.7	18.3
11	5.16	5.32	5.54	5.84	6.33	7.08	7.69	8.49	9.69	10.9	13.3	16.3	20.3
12	5.88	6.05	6.29	6.61	7.14	7.95	8.61	9.47	10.8	12.0	14.7	18.0	22.2
13	6.61	6.80	7.05	7.40	7.97	8.83	9.54	10.5	11.9	13.2	16.1	19.6	24.2
14	7.35	7.56	7.82	8.20	8.80	9.73	10.5	11.5	13.0	14.4	17.5	21.2	26.2
15	8.11	8.33	8.61	9.01	9.65	10.6	11.4	12.5	14.1	15.6	18.9	22.9	28.2
16	8.88	9.11	9.41	9.83	10.5	11.5	12.4	13.5	15.2	16.8	20.3	24.5	30.2
17	9.65	9.89	10.2	10.7	11.4	12.5	13.4	14.5	16.3	18.0	21.7	26.2	32.2
18	10.4	10.7	11.0	11.5	12.2	13.4	14.3	15.5	17.4	19.2	23.1	27.8	34.2
19	11.2	11.5	11.8	12.3	13.1	14.3	15.3	16.6	18.5	20.4	24.5	29.5	36.2
20	12.0	12.3	12.7	13.2	14.0	16.2	16.3	17.6	19.6	21.6	25.9	31.2	38.2

Appendix 1.1
Blocked-Calls-Cleared (Erlang *B*) (*Continued*)

	A, erlangs												
	B												
N	1.0%	1.2%	1.5%	2%	3%	5%	7%	10%	15%	20%	30%	40%	50%
21	12.8	13.1	13.5	14.0	14.9	16.2	17.3	18.7	20.8	22.8	27.3	32.8	40.2
22	13.7	14.0	14.3	14.9	15.8	17.1	18.2	19.7	21.9	24.1	28.7	34.5	42.1
23	14.5	14.8	15.2	15.8	16.7	18.1	19.2	20.7	23.0	25.3	30.1	36.1	44.1
24	15.3	15.6	16.0	16.6	17.6	19.0	20.2	21.8	24.2	26.5	31.6	37.8	46.1
25	16.1	16.5	16.9	17.5	18.5	20.0	21.2	22.8	25.3	27.7	33.0	39.4	48.1
26	17.0	17.3	17.5	18.4	19.4	20.9	22.2	23.9	26.4	28.9	34.4	41.1	50.1
27	17.8	18.2	18.6	19.3	20.3	21.9	23.2	24.9	27.6	30.2	35.8	42.8	52.1
28	18.6	19.0	19.5	20.2	21.2	22.9	24.2	26.0	28.7	31.4	37.2	44.4	54.1
29	19.5	19.9	20.4	21.0	22.1	23.8	25.2	27.1	29.9	32.6	38.6	46.1	56.1
30	20.3	20.7	21.2	21.9	23.1	24.8	26.2	28.1	31.0	33.8	40.0	47.7	58.1
31	21.2	21.6	22.1	22.8	24.0	25.8	27.2	29.2	32.1	35.1	41.5	49.4	60.1
32	22.0	22.5	23.0	23.7	24.9	26.7	28.2	30.2	33.3	36.3	42.9	51.1	62.1
33	22.9	23.3	23.9	24.6	25.8	27.7	29.3	31.3	34.4	37.5	44.3	52.7	64.1
34	23.8	24.2	24.8	25.5	26.8	28.7	30.3	32.4	35.6	38.8	45.7	54.4	66.1
35	24.6	25.1	25.6	26.4	27.7	29.7	31.3	33.4	36.7	40.0	47.1	56.0	68.1
36	25.5	26.0	26.5	27.3	28.6	30.7	32.3	34.5	37.9	41.2	48.6	57.7	70.1
37	26.4	26.8	27.4	28.3	29.6	31.6	33.3	35.6	39.0	42.4	50.0	59.4	72.1
38	27.3	27.7	28.3	29.2	30.5	32.6	34.4	36.6	40.2	43.7	51.4	61.0	74.1
39	28.1	28.6	29.2	30.1	31.5	33.6	35.4	37.7	41.3	44.9	52.8	62.7	76.1
40	29.0	29.5	30.1	31.0	32.4	34.6	36.4	38.8	42.5	46.1	54.2	64.4	78.1

41	29.9	30.4	31.0	31.9	33.4	35.6	37.4	39.9	43.6	47.4	55.7	66.0	80.1
42	30.8	31.3	31.9	32.8	34.3	36.6	38.4	40.9	44.6	48.6	57.1	67.7	82.1
43	31.7	32.2	32.8	33.8	35.3	37.6	39.5	42.0	45.9	49.9	58.5	69.3	84.1
44	32.5	33.1	33.7	34.7	36.2	38.6	40.5	43.1	47.1	51.1	59.9	71.0	86.1
45	33.4	34.0	34.6	35.6	37.2	39.6	41.5	44.2	48.2	52.3	61.3	72.7	88.1
46	34.3	34.9	35.6	36.5	38.1	40.5	42.6	45.2	49.4	53.6	62.8	74.3	90.1
47	35.2	35.8	36.5	37.5	39.1	41.5	43.6	46.3	50.6	54.8	64.2	76.0	92.1
48	36.1	36.7	37.4	38.4	40.0	42.5	44.6	47.4	51.7	56.0	65.6	77.7	94.1
49	37.0	37.6	38.3	39.3	41.0	43.5	45.7	48.5	52.9	57.3	67.0	79.3	96.1
50	37.9	38.5	39.2	40.3	41.9	44.5	46.7	49.6	54.0	58.5	68.5	81.0	98.1
51	38.8	39.4	40.1	41.2	42.9	45.5	47.7	50.6	55.2	59.7	69.9	82.7	100.1
52	39.7	40.3	41.0	42.1	43.9	46.5	48.8	51.7	56.3	61.0	71.3	84.3	102.1
53	40.6	41.2	42.0	43.1	44.8	47.5	49.8	52.8	57.5	62.2	72.7	86.0	104.1
54	41.5	42.1	42.9	44.0	45.8	48.5	50.8	53.9	58.7	63.5	74.2	87.6	106.1
55	42.4	43.0	43.8	44.9	46.7	49.5	51.9	55.0	59.8	64.7	75.6	89.3	108.1
56	43.3	43.9	44.7	45.9	47.7	50.5	52.9	56.1	61.0	65.9	77.0	91.0	110.1
57	44.2	44.8	45.7	46.8	48.7	51.5	53.9	57.1	62.1	67.2	78.4	92.6	112.1
58	45.1	45.8	46.6	47.8	49.6	52.6	55.0	58.2	63.3	68.4	79.8	94.3	114.1
59	46.0	46.7	47.5	48.7	50.6	53.6	56.0	59.3	64.5	69.7	81.3	96.0	116.1
60	46.9	47.6	48.4	49.6	51.6	54.6	57.1	60.4	65.6	70.9	82.7	97.6	118.1
61	47.9	48.5	49.4	50.6	52.5	55.6	58.1	61.5	66.8	72.1	84.1	99.3	120.1
62	48.8	49.4	50.3	51.5	53.5	56.6	59.1	62.6	68.0	73.4	85.5	101.0	122.1
63	49.7	50.4	51.2	52.5	54.5	57.6	60.2	63.7	69.1	74.6	87.0	102.6	124.1
64	50.6	51.3	52.2	53.4	55.4	58.6	61.2	64.8	70.3	75.9	88.4	104.3	126.1
65	51.5	52.2	53.1	54.4	56.4	59.6	62.3	65.8	71.4	77.1	89.8	106.0	128.1
66	52.4	53.1	54.0	55.3	57.4	60.6	63.3	66.9	72.6	78.3	91.2	107.6	130.1
67	53.4	54.1	55.0	56.3	58.4	61.6	64.4	68.0	73.8	79.6	92.7	109.3	132.1
68	54.3	55.0	55.9	57.2	59.3	62.6	65.4	69.1	74.9	80.8	94.1	111.0	134.1
69	55.2	55.9	56.9	58.2	60.3	63.7	66.4	70.2	76.1	82.1	95.5	112.6	136.1
70	56.1	56.8	57.8	59.1	61.3	64.7	67.5	71.3	77.3	83.3	96.9	114.3	138.1

Appendix 1.1
Blocked-Calls-Cleared (Erlang *B*) (*Continued*)

	A, erlangs												
	B												
N	1.0%	1.2%	1.5%	2%	3%	5%	7%	10%	15%	20%	30%	40%	50%
71	57.0	57.8	58.7	60.1	62.3	65.7	68.5	72.4	78.4	84.6	98.4	115.9	140.1
72	58.0	58.7	59.7	61.0	63.2	66.7	69.6	73.5	79.6	85.8	99.8	117.6	142.1
73	58.9	59.6	60.6	62.0	64.2	67.7	70.6	74.6	80.8	87.0	101.2	119.3	144.1
74	59.8	60.6	61.6	62.9	65.2	68.7	71.7	75.6	81.9	88.3	102.7	120.9	146.1
75	60.7	61.5	62.5	63.9	66.2	69.7	72.7	76.7	83.1	89.5	104.1	122.6	148.0
76	61.7	62.4	63.4	64.9	67.2	70.8	73.8	77.8	84.2	90.8	105.5	124.3	150.0
77	62.6	63.4	64.4	65.8	68.1	71.8	74.8	78.9	85.4	92.0	106.9	125.9	152.0
78	63.5	64.3	65.3	66.8	69.1	72.8	75.9	80.0	86.6	93.3	108.4	127.6	154.0
79	64.4	65.2	66.3	67.7	70.1	73.8	76.9	81.1	87.7	94.5	109.8	129.3	156.0
80	65.4	66.2	67.2	68.7	71.1	74.8	78.0	82.2	88.9	95.7	111.2	130.9	158.0
81	66.3	67.1	68.2	69.6	72.1	75.8	79.0	83.3	90.1	97.0	112.6	132.6	160.0
82	67.2	68.0	69.1	70.6	73.0	76.9	80.1	84.4	91.2	98.2	114.1	134.3	162.0
83	68.2	69.0	70.1	71.6	74.0	77.9	81.1	85.5	92.4	99.5	115.5	135.9	164.0
84	69.1	69.9	71.0	72.5	75.0	78.9	82.2	86.6	93.6	100.7	116.9	137.6	166.0
85	70.0	70.9	71.9	73.5	76.0	79.9	83.2	87.7	94.7	102.0	118.3	139.3	168.0
86	70.9	71.8	72.9	74.5	77.0	80.9	84.3	88.8	95.9	103.2	119.8	140.9	170.0
87	71.9	72.7	73.8	75.4	78.0	82.0	85.3	89.9	97.1	104.5	121.2	142.6	172.0
88	72.8	73.7	74.8	76.4	78.9	83.0	86.4	91.0	98.2	105.7	122.6	144.3	174.0
89	73.7	74.6	75.7	77.3	79.9	84.0	87.4	92.1	99.4	106.9	124.0	145.9	176.0
90	74.7	75.6	76.7	78.3	80.9	85.0	88.5	93.1	100.6	108.2	125.5	147.6	178.0

91	75.6	76.5	77.6	79.3	81.9	86.0	89.5	94.2	101.7	109.4	126.9	149.3	180.0
92	76.6	77.4	78.6	80.2	82.9	87.1	90.6	95.3	102.9	110.7	128.3	150.9	182.0
93	77.5	78.4	79.6	81.2	83.9	88.1	91.6	96.4	104.1	111.9	129.7	152.6	184.0
94	78.4	79.3	80.5	82.2	84.9	89.1	92.7	97.5	105.3	113.2	131.2	154.3	186.0
95	79.4	80.3	81.5	83.1	85.8	90.1	93.7	98.6	106.4	114.4	132.6	155.9	188.0
96	80.3	81.2	82.4	84.1	86.8	91.1	94.8	99.7	107.6	115.7	134.0	157.6	190.0
97	81.2	82.2	83.4	85.1	87.8	92.2	95.8	100.8	108.8	116.9	135.5	159.3	192.0
98	82.2	83.1	84.3	86.0	88.8	93.2	96.9	101.9	109.9	118.2	136.9	160.9	194.0
99	83.1	84.1	85.3	87.0	89.8	94.2	97.9	103.0	111.1	119.4	138.3	162.6	196.0
100	84.1	85.0	86.2	88.0	90.8	95.2	99.0	104.1	112.3	120.6	139.7	164.3	198.0
102	85.9	86.9	88.1	89.9	92.8	97.3	101.1	106.3	114.6	123.1	142.6	167.6	202.0
104	87.8	88.8	90.1	91.9	94.8	99.3	103.2	108.5	116.9	125.6	145.4	170.9	206.0
106	89.7	90.7	92.0	93.8	96.7	101.4	105.3	110.7	119.3	128.1	148.3	174.2	210.0
108	91.6	92.6	93.9	95.7	98.7	103.4	107.4	112.9	121.6	130.6	151.1	177.6	214.0
110	93.5	94.5	95.8	97.7	100.7	105.5	109.5	115.1	124.0	133.1	154.0	180.9	218.0
112	95.4	96.4	97.7	99.6	102.7	107.5	111.7	117.3	126.3	135.6	156.9	184.2	222.0
114	97.3	98.3	99.7	101.6	104.7	109.6	113.8	119.5	128.6	138.1	159.7	187.6	226.0
116	99.2	100.2	101.6	103.5	106.7	111.7	115.9	121.7	131.0	140.6	162.6	190.9	230.0
118	101.1	102.1	103.5	105.5	108.7	113.7	118.0	123.9	133.3	143.1	165.4	194.2	234.0
120	103.0	104.0	105.4	107.4	110.7	115.8	120.1	126.1	135.7	145.6	168.3	197.6	238.0
122	104.9	105.9	107.4	109.4	112.6	117.8	122.2	128.3	138.0	148.1	171.1	200.9	242.0
124	106.8	107.9	109.3	111.3	114.6	119.9	124.4	130.5	140.3	150.6	174.0	204.2	246.0
126	108.7	109.8	111.2	113.3	116.6	121.9	126.5	132.7	142.7	153.0	176.8	207.6	250.0
128	110.6	111.7	113.2	115.2	118.6	124.0	128.6	134.9	145.0	155.5	179.7	210.9	254.0
130	112.5	113.6	115.1	117.2	120.6	126.1	130.7	137.1	147.4	158.0	182.5	214.2	258.0
132	114.4	115.5	117.0	119.1	122.6	128.1	132.8	139.3	149.7	160.5	185.4	217.6	262.0
134	116.3	117.4	119.0	121.1	124.6	130.2	134.9	141.5	152.0	163.0	188.3	220.9	266.0
136	118.2	119.4	120.9	123.1	126.6	132.3	137.1	143.7	154.4	165.5	191.1	224.2	270.0
138	120.1	121.3	122.8	125.0	128.6	134.3	139.2	145.9	156.7	168.0	194.0	227.6	274.0
140	122.0	123.2	124.8	127.0	130.6	136.4	141.3	148.1	159.1	170.5	196.8	230.9	278.0

Appendix 1.1
Blocked-Calls-Cleared (Erlang *B*) (*Continued*)

	A, erlangs												
	B												
N	1.0%	1.2%	1.5%	2%	3%	5%	7%	10%	15%	20%	30%	40%	50%
142	123.9	125.1	126.7	128.9	132.6	138.4	143.4	150.3	161.4	173.0	199.7	234.2	282.0
144	125.8	127.0	128.6	130.9	134.6	140.5	145.6	152.5	163.8	175.5	202.5	237.6	286.0
146	127.7	129.0	130.6	132.9	136.6	142.6	147.7	154.7	166.1	178.0	205.4	240.9	290.0
148	129.7	130.9	132.5	134.8	138.6	144.6	149.8	156.9	168.5	180.5	208.2	244.2	294.0
150	131.6	132.8	134.5	136.8	140.6	146.7	151.9	159.1	170.8	183.0	211.1	247.6	298.0
152	133.5	134.8	136.4	138.8	142.6	148.8	154.0	161.3	173.1	185.5	214.0	250.9	302.0
154	135.4	136.7	138.4	140.7	144.6	150.8	156.2	163.5	175.5	188.0	216.8	254.2	306.0
156	137.3	138.6	140.3	142.7	146.6	152.9	158.3	165.7	177.8	190.5	219.7	257.6	310.0
158	139.2	140.5	142.3	144.7	148.6	155.0	160.4	167.9	180.2	193.0	222.5	260.9	314.0
160	141.2	142.5	144.2	146.6	150.6	157.0	162.5	170.2	182.5	195.5	225.4	264.2	318.0
162	143.1	144.4	146.1	148.6	152.7	159.1	164.7	172.4	184.9	198.0	228.2	267.6	322.0
164	145.0	146.3	148.1	150.6	154.7	161.2	166.8	174.6	187.2	200.4	231.1	270.9	326.0
166	146.9	148.3	150.0	152.6	156.7	163.3	168.9	176.8	189.6	202.9	233.9	274.2	330.0
168	148.9	150.2	152.0	154.5	158.7	165.3	171.0	179.0	191.9	205.4	236.8	277.6	334.0
170	150.8	152.1	153.9	156.5	160.7	167.4	173.2	181.2	194.2	207.9	239.7	280.9	338.0
172	152.7	154.1	155.9	158.5	162.7	169.5	175.3	183.4	196.6	210.4	242.5	284.2	342.0
174	154.6	156.0	157.8	160.4	164.7	171.5	177.4	185.6	198.9	212.9	245.4	267.6	346.0
176	156.6	158.0	159.8	162.4	166.7	173.6	179.6	187.8	201.3	215.4	248.2	290.9	350.0
178	158.5	159.9	161.8	164.4	168.7	175.7	181.7	190.0	203.6	217.9	251.1	294.2	354.0
180	160.4	161.8	163.7	166.4	170.7	177.8	183.8	192.2	206.0	220.4	253.9	297.5	358.0
182	162.3	163.6	165.7	168.3	172.8	179.8	185.9	194.4	208.3	222.9	256.8	300.9	362.0
184	164.3	165.7	167.6	170.3	174.8	181.9	188.1	196.6	210.7	225.4	259.6	304.2	366.0
186	166.2	167.7	169.6	172.3	176.8	184.0	190.2	198.9	213.0	227.9	262.5	307.5	370.0
188	168.1	169.6	171.5	174.3	178.8	186.1	192.3	201.1	215.4	230.4	265.4	310.9	374.0
190	170.1	171.5	173.5	176.3	180.8	188.1	194.5	203.3	217.7	232.9	268.2	314.2	378.0

192	172.0	173.5	175.4	178.2	182.8	190.2	196.6	205.5	220.1	235.4	271.1	317.5	382.0
194	173.9	175.4	177.4	180.2	184.8	192.3	198.7	207.7	222.4	237.9	273.9	320.9	386.0
196	175.9	177.4	179.4	182.2	186.9	194.4	200.8	209.9	224.8	240.4	276.8	324.2	390.0
198	177.8	179.3	181.3	184.2	188.9	196.4	203.0	212.1	227.1	242.9	279.6	327.5	394.0
200	179.7	181.3	183.3	186.2	190.9	198.5	205.1	214.3	229.4	245.4	282.5	330.9	398.0
202	181.7	183.2	185.2	188.1	192.9	200.6	207.2	216.5	231.8	247.9	285.4	334.2	402.0
204	183.6	185.2	187.2	190.1	194.9	202.7	209.4	218.7	234.1	250.4	288.2	337.5	406.0
206	185.5	187.1	189.2	192.1	196.9	204.7	211.5	221.0	236.5	252.9	291.1	340.9	410.0
208	187.5	189.1	191.1	194.1	199.0	206.8	213.6	223.2	238.8	255.4	293.9	344.2	414.0
210	189.4	191.0	193.1	196.1	201.0	208.9	215.6	225.4	241.2	257.9	296.8	347.5	418.0
212	191.4	193.0	195.1	198.1	203.0	211.0	217.9	227.6	243.5	260.4	299.6	350.9	422.0
214	193.3	194.9	197.0	200.0	205.0	213.0	220.0	229.8	245.9	262.9	302.5	354.2	426.0
216	195.2	196.9	199.0	202.0	207.0	215.1	222.2	232.0	248.2	265.4	305.3	357.5	430.0
218	197.2	198.8	201.0	204.0	209.1	217.2	224.3	234.2	250.6	267.9	308.2	360.9	434.0
220	199.1	200.8	202.9	206.0	211.1	219.3	226.4	236.4	252.9	270.4	311.1	364.2	438.0
222	201.1	202.7	204.9	208.0	213.1	221.4	228.6	238.6	255.3	272.9	313.9	367.5	442.0
224	203.0	204.7	206.8	210.0	215.1	223.4	230.7	240.9	257.6	275.4	316.8	370.9	446.0
226	204.9	206.6	208.8	212.0	217.1	225.5	232.8	243.1	260.0	277.8	319.6	374.2	450.0
228	206.9	208.6	210.8	213.9	219.2	227.6	235.0	245.3	262.3	280.3	322.5	377.5	454.0
230	208.8	210.5	212.8	215.9	221.2	229.7	237.1	247.5	264.7	282.8	325.3	380.9	458.0
232	210.8	212.5	214.7	217.9	223.2	231.8	239.2	249.7	267.0	285.3	328.2	384.2	462.0
234	212.7	214.4	216.7	219.9	225.2	233.8	241.4	251.9	269.4	287.8	331.1	387.5	466.0
236	214.7	216.4	218.7	221.9	227.2	235.9	243.5	254.1	271.7	290.3	333.9	390.9	470.0
238	216.6	218.3	220.6	223.9	229.3	238.0	245.6	256.3	274.1	292.8	336.8	394.2	474.0
240	218.6	220.3	222.6	225.9	231.3	240.1	247.8	258.6	276.4	295.3	339.6	397.5	478.0
242	220.5	222.3	224.6	227.9	233.3	242.2	249.9	260.8	278.8	297.8	342.5	400.9	482.0
244	222.5	224.2	226.5	229.9	235.3	244.3	252.0	263.0	281.1	300.3	345.3	404.2	486.0
246	224.4	226.2	228.5	231.8	237.4	246.3	254.2	265.2	283.4	302.8	348.2	407.5	490.0
248	226.3	228.1	230.5	233.8	239.4	248.4	256.3	267.4	285.8	305.3	351.0	410.9	494.0
250	228.3	230.1	232.5	235.8	241.4	250.5	258.4	269.6	288.1	307.8	353.9	414.2	498.0
	.976	*.982*	*.988*	*.998*	*1.014*	*1.042*	*1.070*	*1.108*	*1.176*	*1.250*	*1.428*	*1.666*	*2.000*

Appendix 1.1
Blocked-Calls-Cleared (Erlang *B*) (*Continued*)

	A, erlangs												
	B												
N	1.0%	1.2%	1.5%	2%	3%	5%	7%	10%	15%	20%	30%	40%	50%
300	277.1	279.2	281.9	285.7	292.1	302.6	311.9	325.0	346.9	370.3	425.3	497.5	598.0
	.982	*.984*	*.990*	*1.000*	*1.016*	*1.044*	*1.070*	*1.108*	*1.174*	*1.248*	*1.428*	*1.668*	*2.000*
350	326.2	328.4	331.4	335.7	342.9	354.8	365.4	380.4	405.6	432.7	496.7	580.9	698.0
	.982	*.988*	*.994*	*1.004*	*1.020*	*1.046*	*1.070*	*1.108*	*1.176*	*1.250*	*1.430*	*1.666*	*2.000*
400	375.3	377.8	381.1	385.9	393.9	407.1	418.9	435.8	464.4	495.2	568.2	664.2	798.0
	.986	*.990*	*.996*	*1.004*	*1.018*	*1.046*	*1.072*	*1.110*	*1.176*	*1.250*	*1.428*	*1.666*	*2.000*
450	424.6	427.3	430.9	436.1	444.8	459.4	472.5	491.3	523.2	557.7	639.6	747.5	898.0
	.988	*.994*	*.998*	*1.006*	*1.022*	*1.048*	*1.070*	*1.108*	*1.176*	*1.250*	*1.428*	*1.668*	*2.000*
500	474.0	477.0	480.8	486.4	495.9	511.8	526.0	546.7	582.0	620.2	711.0	830.9	998.0
	.991	*.994*	*1.000*	*1.008*	*1.022*	*1.047*	*1.073*	*1.110*	*1.176*	*1.249*	*1.429*	*1.666*	*2.000*
600	573.1	576.4	580.8	587.2	598.1	616.5	633.3	657.7	699.6	745.1	853.9	997.5	1198.
	.993	*.997*	*1.002*	*1.010*	*1.024*	*1.049*	*1.073*	*1.110*	*1.176*	*1.250*	*1.428*	*1.665*	*2.00*
700	672.4	676.1	681.0	688.2	700.5	721.4	740.6	768.7	817.2	870.1	996.7	1164.	1398.
	.994	*.998*	*1.004*	*1.011*	*1.025*	*1.050*	*1.073*	*1.110*	*1.176*	*1.250*	*1.433*	*1.67*	*2.00*
800	771.8	775.9	781.4	789.3	803.0	826.4	847.9	879.7	934.8	985.1	1140.	1331.	1598.
	.997	*1.000*	*1.004*	*1.013*	*1.025*	*1.050*	*1.074*	*1.111*	*1.172*	*1.249*	*1.42*	*1.67*	*2.00*
900	871.5	875.9	881.8	890.6	905.5	931.4	955.3	990.8	1052.	1120.	1282.	1498.	1798.
	.997	*1.001*	*1.006*	*1.013*	*1.026*	*1.046*	*1.077*	*1.112*	*1.18*	*1.25*	*1.43*	*1.66*	*2.00*
1000	971.2	976.0	982.4	991.9	1008.	1036.	1063.	1102.	1170.	1245.	1425.	1664.	1998.
	.998	*1.000*	*1.006*	*1.011*	*1.03*	*1.05*	*1.07*	*1.11*	*1.18*	*1.25*	*1.43*	*1.67*	*2.00*
1100	1071.	1076.	1083.	1093.	1111.	1141.	1170.	1213.	1288.	1370.	1568.	1831.	2198.

SOURCE: After Lee, Ref. 5, pp. 258–265.

Appendix 1.2 Status of First 90 Cities (1993) Key: A—Band A Carrier; B—Band B Carrier

MSA no./name		System operators	On-line status	Rank (based on number of subscribers)	Switching equipment
1. New York, NY	B	Nynex Mobile	6/15/84		AT&T
	A	Cellular One	4/5/86	2	Motorola
2. Los Angeles, CA	B	PacTel Cellular	6/13/84		Motorola
	A	LA Cellular Telephone	3/27/87	1	Ericsson
3. Chicago, IL	B	Ameritech Mobile	10/13/83		AT&T
	A	Cellular One	1/3/85	3	Ericsson
4. Philadelphia, PA	B	Bell Atlantic Mobile	7/12/84		AT&T
	A	Metrophone	2/12/85	8	Motorola
5. Detroit, MI	B	Ameritech Mobile	5/21/84		AT&T
	A	Cellular One	7/30/85	5	Ericsson
6. Boston, MA	B	Nynex Mobile	1/1/85		AT&T
	A	Cellular One	1/1/85	11	Motorola
7. San Francisco, CA	B	GTE Mobilnet	4/2/85		Motorola
(ranked with San Jose)	A	Cellular One	9/26/86	9	Ericsson
8. Washington, DC	B	Bell Atlantic Mobile	4/2/84		AT&T
(ranked with Baltimore)	A	Cellular One	12/16/83	4	Motorola
9. Dallas, TX	B	Southwestern Bell Mobile	7/31/84		AT&T
	A	MetroCel	3/1/86	6	Motorola
10. Houston, TX	B	GTE Mobilnet	9/28/84		Motorola
	A	Houston Cellular Telephone	6/16/86	10	Ericsson
11. St. Louis, MO	B	Southwestern Bell Mobile	7/. ./84		AT&T
	A	CyberTel	7/16/84	18	Motorola
12. Miami, FL	B	BellSouth Mobility	5/25/84		AT&T
	A	Cellular One	3/6/87	7	NTI/GE
13. Pittsburgh, PA	B	Bell Atlantic Mobile	12/10/84		AT&T
	A	Cellular One/McCaw		26	Ericsson
14. Baltimore, MD	B	Bell Atlantic Mobile	4/2/84		AT&T
	A	Cellular One	12/16/83	4	Motorola
15. Minneapolis, MN	B	U.S. West	6/6/84		GE/Motorola
	A	Cellular One	7/23/84	19	NTI/GE
16. Cleveland, OH	B	GTE Mobilnet	12/18/84		Motorola
	A	Cellular One	5/31/85	14	NTI/GE
17. Atlanta, GA	B	BellSouth Mobility	9/5/84		AT&T
	A	PacTel Cellular	2/1/88	12	Motorola
18. San Diego, CA	B	PacTel Cellular	8/15/85		AT&T
	A	U.S. West	4/1/86	16	Motorola
19. Denver, CO	B	U.S. West	7/10/84		NTI/GE
	A	Cellular One	11/21/86	21	AT&T/Panasonic

Appendix 1.2 Status of First 90 Cities (1993) Key: A—Band A Carrier; B—Band B Carrier (*Continued*)

MSA no./name		System operators	On-line status	Rank (based on number of subscribers)	Switching equipment
20. Seattle, WA	B	U.S. West	7/12/84		NTI/GE
	A	Cellular One	12/12/85	13	AT&T
21. Milwaukee, WI	B	Ameritech Mobile	6/1/84		AT&T
	A	Cellular One	6/1/84	30	Ericsson
22. Tampa, FL	B	GTE Mobilnet	11/30/84		Motorola
	A	Cellular One	9/25/87	15	Ericsson
23. Cincinnati, OH	B	Ameritech Mobile	11/5/84		AT&T
	A	Cellular One	8/26/86	22	Ericsson
24. Kansas City, MO	B	Southwestern Bell Mobile	8/14/84		Motorola
	A	Cellular One	2/14/86	27	AT&T
25. Buffalo, NY	B	Nynex Mobile	4/16/84		Motorola
	A	Cellular One	6/1/84	35	Ericsson
26. Phoenix, AZ	B	U.S. West	8/15/84		AT&T
	A	Bell Atlantic Mobile	3/1/86	17	Motorola
27. San Jose, CA	B	GTE Mobilnet	4/2/85		Motorola
	A	Cellular One	9/25/86	9	Ericsson
28. Indianapolis, IN	B	GTE Mobilnet	6/3/84		AT&T
	A	Cellular One	2/3/84	20	Ericsson
29. New Orleans, LA	B	BellSouth Mobility	9/1/84		Motorola
	A	Radiofone	9/6/85	36	Motorola
30. Portland, OR	B	GTE Mobilnet	3/5/85		AT&T
	A	Cellular One	7/12/85	25	Ericsson
31. Columbus, OH	B	Ameritech Mobile	6/30/85		NTI/GE
	A	Cellular One	7/1/86	34	NTI
32. Hartford, CT	B	SNET Cellular	1/31/85		AT&T
	A	Bell Atlantic Mobile	10/16/87	37	Motorola
33. San Antonio, TX	B	Southwestern Bell Mobile	1/28/85		AT&T
	A	Cellular One	10/21/86	29	
34. Rochester, NY	B	Rochester Telephone Mobile	6/4/86		AT&T
	A	Genesee Telephone Co.	9/22/86	—	Ericsson
35. Sacramento, CA	B	PacTel Cellular	8/29/85		Motorola
	A	Cellular One	10/30/87	24	Ericsson
36. Memphis, TN	B	BellSouth Mobility	5/1/85		Motorola
	A	Cellular One	12/24/86	38	AT&T
37. Louisville, KY	B	BellSouth Mobility	1/3/85		Motorola
	A	Cellular One	2/15/85	—	AT&T
38. Providence, RI	B	Nynex Mobile	8/22/85		AT&T
	A	Bell Atlantic Mobile	7/6/87	31	Motorola
39. Salt Lake City, UT	B	U.S. West	1/29/85		AT&T
	A	Cellular One	12/17/86	39	Motorola/NEC/NovAtel
40. Dayton, OH	B	Ameritech Mobile	5/31/85		NTI/GE
	A	Cellular One	8/26/86	—	Northern Telecom

Appendix 1.2 Status of First 90 Cities (1993) Key: A—Band A Carrier; B—Band B Carrier (*Continued*)

MSA no./name		System operators	On-line status	Rank (based on number of subscribers)	Switching equipment
41. Birmingham, AL	B	BellSouth Mobility	9/26/85		Motorola
	A	Cellular One	12/31/86	—	AT&T
42. Bridgeport, CT	B	Southern New England Tele.	5/20/85		AT&T
	A	Bell Atlantic Mobile	11/20/87	—	Motorola
43. Norfolk, VA	B	Cellular One	5/3/85		AT&T
	A	Centel Cellular	11/1/85	33	Motorola
44. Albany, NY	B	Nynex Mobile	6/25/85		NTI/GE
	A	Cellular One	12/3/86	—	Northern Telecom/ Ericsson
45. Oklahoma City, OK	B	Southwestern Bell Mobile	1/14/85		AT&T
	A	Cellular One	1/17/86	—	AT&T
46. Nashville, TN	B	BellSouth Mobility	6/10/85		Motorola
	A	Cellular One	6/30/87	—	AT&T
47. Greensboro, NC	B	Centel	5/15/85		Motorola
	A	Cellular One	12/27/85	—	Motorola
48. Toledo, OH	B	Centel Cellular	7/25/85		Motorola
	A	Cellular One/PacTel Cellular	4/15/86	—	Ericsson
49. New Haven, CT	B	Southern New England Tele.	3/4/85		AT&T
	A	Bell Atlantic Mobile	11/20/87	—	Motorola
50. Honolulu, HI	B	GTE Mobilnet	3/26/84		Motorola
	A	Honolulu Cellular Telephone	6/1/86	—	Ericsson
51. Jacksonville, FL	B	BellSouth Mobility	6/12/85		Motorola
	A	Cellular One	8/14/87	40	Ericsson
52. Akron, OH	B	GTE Mobilnet	10/31/85		Motorola
	A	Cellular One	12/15/86	—	Motorola
53. Syracuse, NY	B	Nynex Mobile	1/24/86		AT&T
	A	Cellular One	12/31/85	—	Motorola
54. Gary, IN	B	Ameritech Mobile	3/11/85		AT&T
	A	Cellular One	4/21/86	—	Ericsson
55. Worcester, MA	B	Nynex Mobile	11/18/85		AT&T
	A	Cellular One	11/18/85	—	Motorola
56. Northeast, PA	B	Cellular Plus	7/2/85		AT&T
	A	Cellular One	12/31/86	—	NTI/GE
57. Tulsa, OK	B	United States Cellular	8/30/85		NEC
	A	Cellular One	5/22/86	—	AT&T
58. Allentown, PA	B	Bell Atlantic Mobile	3/18/85		AT&T
	A	Cellular One	10/18/85	—	NTI/GE
59. Richmond, VA	B	Contel Cellular, Inc.	5/10/85		AT&T
	A	Cellular One	12/2/86	—	Motorola
60. Orlando, FL	B	BellSouth Mobility	2/27/85		Astronet
	A	Cellular One	12/29/86	32	Ericsson
61. Charlotte, NC	B	Alltel	4/15/85		Motorola
	A	Bell Atlantic Mobile	3/1/86	23	Motorola

Appendix 1.2 Status of First 90 Cities (1993) Key: A—Band A Carrier; B—Band B Carrier (*Continued*)

MSA no./name		System operators	On-line status	Rank (based on number of subscribers)	Switching equipment
62. New Brunswick, NJ	B	Nynex Mobile	1/21/87		AT&T
	A	Cellular One	11/1/86	—	Motorola
63. Springfield, MA	B	Nynex Mobile	4/10/87		AT&T
	A	Springfield Cellular Telephone	10/16/87	—	Motorola
64. Grand Rapids, MI	B	Century Cellunet	9/17/86		AT&T
	A	Cellular One	6/16/86	—	Ericsson
65. Omaha, NE	B	Centel Cellular	4/15/85		Motorola
	A	U.S. West Cellular	12/23/85	—	NTI
66. Youngstown, OH	B	Centel Cellular	9/19/85		Motorola
	A	Youngstown Cellular/Wilcom	12/23/86	—	Northern Telecom
67. Greenville, SC	B	Centel Cellular	7/30/86		Motorola
	A	Bell Atlantic Mobile	8/18/86	—	Motorola
68. Flint, MI	B	Ameritech Mobile	7/12/85		AT&T
	A	Cellular One	7/30/85	—	Ericsson
69. Wilmington, DE	B	Bell Atlantic Mobile	3/27/85		AT&T
	A	Cellular One	5/86	—	Motorola
70. Long Branch, NJ	B	Nynex Mobile	2/20/87		AT&T
	A	Cellular One	11/1/86	—	Motorola
71. Raleigh-Durham, NC	B	Centel Cellular	11/11/85		Motorola
	A	Cellular One	9/16/85	—	NTI/GE
72. W. Palm Beach, FL	B	BellSouth Mobility	5/23/85		AT&T
	A	Cellular One	3/6/87	—	
73. Oxnard, CA	B	PacTel Mobile Access	10/30/85		AT&T
	A	Ventura Cellular	9/87	—	Ericsson
74. Fresno, CA	B	Contel Cellular	5/1/86		AT&T
	A	Cellular One	10/23/87	—	Ericsson
75. Austin, TX	B	GTE Mobilnet	9/27/85		Motorola
	A	Cellular One	12/27/85	—	AT&T
76. New Bedford, MA	B	Nynex Mobile	12/9/85		AT&T
	A	Bell Atlantic Mobile	7/8/87	—	Motorola
77. Tucson, AZ	B	U.S. West	8/6/85		NTI/GE
	A	Bell Atlantic Mobile	4/1/86	—	Motorola
78. Lansing, MI	B	Century Cellunet	9/16/87		Motorola
	A	Cellular One	9/17/86	—	Ericsson
79. Knoxville, TN	B	United States Cellular	7/23/85		NEC
	A	Cellular One	12/22/87	—	AT&T
80. Baton Rouge, LA	B	BellSouth Mobility	7/2/85		Motorola
	A	Cellular One	8/1/86	—	Motorola
81. El Paso, TX	B	Contel Cellular	2/25/86		AT&T
	A	Bell Atlantic Mobile	5/2/86	—	Motorola
82. Tacoma, WA	B	U.S. West	4/16/85		NTI/GE
	A	Cellular One	12/12/85	—	AT&T

Appendix 1.2 Status of First 90 Cities (1993) Key: A—Band A Carrier; B—Band B Carrier *(Continued)*

MSA no./name		System operators	On-line status	Rank (based on number of subscribers)	Switching equipment
83. Mobile, AL	B	GTE of Mobile	9/3/85		AT&T
	A	BellSouth Mobility	6/3/87	—	Astronet
84. Harrisburg, PA	B	United Telespectrum	10/18/85		Motorola
	A	Cellular One	9/18/86	—	NTI/GE
85. Johnson City, TN	B	Centel	10/3/85		Motorola
	A	U.S. West	1/22/88	—	AT&T
86. Albuquerque, NM	B	U.S. West	8/13/85		NTI/GE
	A	Bell Atlantic Mobile	11/1/85	—	Motorola
87. Canton, OH	B	GTE Mobilnet	2/25/87		Motorola
	A	Cellular One	2/2/87	—	NTI/GE
88. Chattanooga, TN	B	BellSouth Mobility	8/1/85		Motorola
	A	Cellular One	11/20/87	—	AT&T
89. Wichita, KS	B	Southwestern Bell Mobile	2/11/85		Motorola
	A	Cellular One	1/24/86	—	Mitsubishi/NEC/ Motorola/Novatel
90. Charleston, SC	B	Contel Cellular	9/11/85		Motorola
	A	Cellular One	1/22/88	—	NTI/GE

Appendix 1.3 List of MSAs and RSAs

1. New York, NY
2. Los Angeles, CA
3. Chicago, IL
4. Philadelphia, PA
5. Detroit, MI
6. Boston, MA-NH
7. San Francisco, CA
8. Washington, DC
9. Dallas, TX
10. Houston, TX
11. St. Louis, MO
12. Miami, FL
13. Pittsburgh, PA
14. Baltimore, MD
15. Minneapolis, MN-WI
16. Cleveland, OH
17. Atlanta, GA
18. San Diego, CA
19. Denver, CO
20. Seattle, WA
21. Milwaukee, WI
22. Tampa, FL
23. Cincinnati, OH
24. Kansas City, MO
25. Buffalo, NY
26. Phoenix, AZ
27. San Jose, CA
28. Indianapolis, IN
29. New Orleans, LA
30. Portland, OR-WA
31. Columbus, OH
32. Hartford, CT
33. San Antonio, TX
34. Rochester, NY
35. Sacramento, CA
36. Memphis, TN
37. Louisville, KY
38. Providence, RI
39. Salt Lake City, UT
40. Dayton, OH
41. Birmingham, AL
42. Bridgeport, CT
43. Norfolk, VA
44. Albany, NY
45. Oklahoma City, OK
46. Nashville, TN
47. Greensboro, NC
48. Toledo, OH
49. New Haven, CT
50. Honolulu, HI
51. Jacksonville, FL
52. Akron, OH
53. Syracuse, NY
54. Gary, IN
55. Worcester, MA
56. Northeast, PA
57. Tulsa, OK
58. Allentown, PA-NJ
59. Richmond, VA
60. Orlando, FL
61. Charlotte, NC
62. New Brunswick, NJ
63. Springfield, MA
64. Grand Rapids, MI
65. Omaha, NE
66. Youngstown, OH
67. Greenville, SC
68. Flint, MI
69. Wilmington, DE-NJ-MD
70. Long Branch, NJ
71. Raleigh-Durham, NC
72. W. Palm Beach, FL
73. Oxnard, CA
74. Fresno, CA
75. Austin, TX
76. New Bedford, MA
77. Tucson, AZ
78. Lansing, MI
79. Knoxville, TN
80. Baton Rouge, LA
81. El Paso, TX
82. Tacoma, WA
83. Mobile, AL
84. Harrisburg, PA
85. Johnson City, TN-VA
86. Albuquerque, NM
87. Canton, OH
88. Chattanooga, TN
89. Wichita, KS
90. Charleston, SC
91. San Juan, PR
92. Little Rock, AR
93. Las Vegas, NV
94. Saginaw Bay–Midland, MI
95. Columbia, SC
96. Fort Wayne, IN
97. Bakersfield, CA
98. Davenport, IA-Mol., IL
99. York, PA
100. Shreveport, LA
101. Beaumont, TX
102. Des Moines, IA
103. Peoria, IL
104. Newport News, VA
105. Lancaster, PA
106. Jackson, MS
107. Stockton, CA
108. Augusta, GA-SC
109. Spokane, WA
110. Huntington-Ashland, WV
111. Vallejo, CA
112. Corpus Christi, TX
113. Madison, WI
114. Lakeland, FL
115. Utica-Rome, NY
116. Lexington-Fayette, KY
117. Colorado Springs, CO
118. Reading, PA
119. Evansville, IN
120. Huntsville, AL
121. Trenton, NJ
122. Binghamton, NY
123. Santa Rosa-Petaluma, CA
124. Santa Barbara, CA
125. Appleton, WI
126. Salinas, CA
127. Pensacola, FL
128. McAllen, TX
129. South Bend, IN
130. Erie, PA
131. Rockford, IL
132. Kalamazoo, MI
133. Manchester-Nashua, NH
134. Atlantic City, NJ
135. Eugene-Springfield, OR
136. Lorain-Elyria, OH
137. Melbourne, FL
138. Macon, GA
139. Montgomery, AL
140. Charleston, WV
141. Duluth, MN
142. Modesto, CA
143. Johnstown, PA
144. Orange County, NY
145. Hamilton, OH
146. Daytona Beach, FL
147. Ponce, PR
148. Salem, OR
149. Fayetteville, NC
150. Visalia-Tulare, CA
151. Poughkeepsie, NY
152. Portland, ME
153. Columbus, GA
154. New London-Norwich, CT
155. Savannah, GA
156. Portsmouth, NH
157. Roanoke, VA
158. Lima, OH
159. Provo-Orem, UT
160. Killeen-Temple, TX
161. Lubbock, TX
162. Brownsville, TX
163. Springfield, MO
164. Fort Myers, FL
165. Fort Smith, AR-OK
166. Hickory, NC
167. Sarasota, FL
168. Tallahassee, FL
169. Mayaguez, PR
170. Galveston, TX
171. Reno, NV
172. Lincoln, NE
173. Biloxi-Gulfport, MS
174. Lafayette, LA
175. Santa Cruz, CA
176. Springfield, IL
177. Battle Creek, MI
178. Wheeling, WV-OH
179. Topeka, KS
180. Springfield, OH
181. Muskegon, MI
182. Fayetteville-Springdl., AR
183. Asheville, NC
184. Houma-Thibodaux, LA
185. Terre Haute, IN
186. Green Bay, WI
187. Anchorage, AK
188. Amarillo, TX
189. Racine, WI
190. Boise City, ID
191. Yakima, WA
192. Gainesville, FL
193. Benton Harbor, MI
194. Waco, TX
195. Cedar Rapids, IA
196. Champaign-Urbana, IL
197. Lake Charles, LA
198. St. Cloud, MN
199. Steubenville-Weirton, OH
200. Parkersburg-Marietta, WV
201. Waterloo-Cedar Falls, IA
202. Arecibo, PR
203. Lynchburg, VA
204. Aguadilla, PR
205. Alexandria, LA
206. Longview-Marshall, TX
207. Jackson, MI
208. Fort Pierce, FL

Appendix 1.3 List of MSAs and RSAs (*Continued*)

209. Clarksville, TN-KY
210. Fort Collins-Loveland, CO
211. Bradenton, FL
212. Bremerton, WA
213. Pittsfield, MA
214. Richland-Kennewick, WA
215. Chico, CA
216. Janesville-Beloit, WI
217. Anderson, IN
218. Wilmington, NC
219. Monroe, LA
220. Abilene, TX
221. Fargo-Moorhead, ND-MN
222. Tuscaloosa, AL
223. Elkhart-Goshen, IN
224. Bangor, ME
225. Altoona, PA
226. Florence, AL
227. Anderson, SC
228. Vineland-Millville, NJ
229. Medford, OR
230. Decatur, IL
231. Mansfield, OH
232. Eau Claire, WI
233. Wichita Falls, TX
234. Athens, GA
235. Petersburg, VA
236. Muncie, IN
237. Tyler, TX
238. Sharon, PA
239. Joplin, MO
240. Texarkana, TX-AR
241. Pueblo, CO
242. Olympia, WA
243. Greeley, CO
244. Kenosha, WI
245. Ocala, FL
246. Dothan, AL
247. Lafayette, IN
248. Burlington, VT
249. Anniston, AL
250. Bloomington-Normal, IL
251. Williamsport, PA
252. Pascagoula, MS
253. Sioux City, IA-NE
254. Redding, CA
255. Odessa, TX
256. Charlottesville, VA
257. Hagerstown, MD
258. Jacksonville, NC
259. State College, PA
260. Lawton, OK
261. Albany, GA
262. Danville, VA
263. Wausau, WI
264. Florence, SC
265. Fort Walton Beach, FL
266. Glens Falls, NY
267. Sioux Falls, SD
268. Billings, MT
269. Cumberland, MD-WV
270. Bellingham, WA
271. Kokomo, IN
272. Gadsden, AL
273. Kankakee, IL
274. Yuba City, CA
275. St. Joseph, MO
276. Grand Forks, ND
277. Sheboygan, WI
278. Columbia, MO
279. Lewiston-Auburn, ME
280. Burlington, NC
281. Laredo, TX
282. Bloomington, IN
283. Panama City, FL
284. Elmira, NY
285. Las Cruces, NM
286. Dubuque, IA
287. Bryan-College Station, TX
288. Rochester, MN
289. Rapid City, SD
290. La Crosse, WI
291. Pine Bluff, AR
292. Sherman-Denison, TX
293. Owensboro, KY
294. San Angelo, TX
295. Midland, TX
296. Iowa City, IA
297. Great Falls, MT
298. Bismarck, ND
299. Casper, WY
300. Victoria, TX
301. Lawrence, KS
302. Enid, OK
303. Aurora-Elgin, IL
304. Joliet, IL
305. Alton-Granite City, IL
307. Franklin, AL-1
308. Jackson, AL-2
309. Lamar, AL-3
310. Bib, AL-4
311. Cleburne, AL-5
312. Washington, AL-6
313. Butler, AL-7
314. Lee, AL-8
315. Wade Hampton, AK-1
316. Bethel, AK-2
317. Haines, AK-3
318. Mohave, AZ-1
319. Coconino, AZ-2
320. Navajo, AZ-3
321. Yuma, AZ-4
322. Gila, AZ-5
323. Graham, AZ-6
324. Madison, AR-1
325. Marion, AR-2
326. Sharp, AR-3
327. Clay, AR-4
328. Cross, AR-5
329. Cleburne, AR-6
330. Pope, AR-7
331. Franklin, AR-8
332. Polk, AR-9
333. Garland, AR-10
334. Hempstead, AR-11
335. Ouachita, AR-12
336. Del Norte, CA-1
337. Modoc, CA-2
338. Alpine, CA-3
339. Madera, CA-4
340. San Luis Obispo, CA-5
341. Mono, CA-6
342. Imperial, CA-7
343. Tehama, CA-8
344. Mendocino, CA-9
345. Sierra, CA-10
346. El Dorado, CA-11
347. Kings, CA-12
348. Moffat, CO-1
349. Logan, CO-2
350. Garfield, CO-3
351. Park, CO-4
352. Elbert, CO-5
353. San Miguel, CO-6
354. Saguache, CO-7
355. Kiowa, CO-8
356. Costilla, CO-9
357. Litchfield, CT-1
358. Windham, CT-2
359. Kent, DE-1
360. Collier, FL-1
361. Glades, FL-2
362. Hardee, FL-3
363. Citrus, FL-4
364. Putnam, FL-5
365. Dixie, FL-6
366. Hamilton, FL-7
367. Jefferson, FL-8
368. Calhoun, FL-9
369. Walton, FL-10
370. Monroe, FL-11
371. Whitfield, GA-1
372. Dawson, GA-2
373. Chattooga, GA-3
374. Jasper, GA-4
375. Haralson, GA-5
376. Spalding, GA-6
377. Hancock, GA-7
378. Warren, GA-8
379. Marion, GA-9
380. Bleckley, GA-10
381. Toombs, GA-11
382. Liberty, GA-12
383. Early, GA-13
384. Worth, GA-14
385. Kauai, HI-1
386. Maui, HI-2
387. Hawaii, HI-3
388. Boundary, ID-1
389. Idaho, ID-2
390. Lemhi, ID-3
391. Elmore, ID-4
392. Butte, ID-5
393. Clark, ID-6
394. Jo Daviess, IL-1
395. Bureau, IL-2
396. Mercer, IL-3
397. Adams, IL-4
398. Mason, IL-5
399. Montgomery, IL-6
400. Vermilion, IL-7
401. Washington, IL-8
402. Clay, IL-9
403. Newton, IN-1
404. Kosciusko, IN-2
405. Huntington, IN-3
406. Miami, IN-4
407. Warren, IN-5
408. Randolph, IN-6
409. Owen, IN-7
410. Brown, IN-8
411. Decatur, IN-9
412. Mills, IA-1
413. Union, IA-2
414. Monroe, IA-3
415. Muscatine, IA-4
416. Jackson, IA-5
417. Iowa, IA-6

Appendix 1.3 List of MSAs and RSAs
(Continued)

418. Audubon, IA-7
419. Monona, IA-8
420. Ida, IA-9
421. Humboldt, IA-10
422. Hardin, IA-11
423. Winneshiek, IA-12
424. Mitchell, IA-13
425. Kossuth, IA-14
426. Dickinson, IA-15
427. Lyon, IA-16
428. Cheyenne, KS-1
429. Norton, KS-2
430. Jewell, KS-3
431. Marshall, KS-4
432. Brown, KS-5
433. Wallace, KS-6
434. Trego, KS-7
435. Ellsworth, KS-8
436. Morris, KS-9
437. Franklin, KS-10
438. Hamilton, KS-11
439. Hodgeman, KS-12
440. Edwards, KS-13
441. Reno, KS-14
442. Elk, KS-15
443. Fulton, KY-1
444. Union, KY-2
445. Meade, KY-3
446. Spencer, KY-4
447. Barren, KY-5
448. Madison, KY-6
449. Trimble, KY-7
450. Mason, KY-8
451. Elliott, KY-9
452. Powell, KY-10
453. Clay, KY-11
454. Claiborne, LA-1
455. Morehouse, LA-2
456. De Soto, LA-3
457. Caldwell, LA-4
458. Beauregard, LA-5
459. Iberville, LA-6
460. West Feliciana, LA-7
461. St. James, LA-8
462. Plaquemines, LA-9
463. Oxford, ME-1
464. Somerset, ME-2
465. Kennebec, ME-3
466. Washington, ME-4
467. Garrett, MD-1
468. Kent, MD-2
469. Frederick, MD-3
470. Franklin, MA-1
471. Barnstable, MA-2
472. Gogebic, MI-1
473. Alger, MI-2
474. Emmet, MI-3
475. Cheboygan, MI-4
476. Manistee, MI-5
477. Roscommon, MI-6
478. Newaygo, MI-7
479. Allegan, MI-8
480. Cass, MI-9
481. Tuscola, MI-10
482. Kittson, MN-1
483. Lake of the Woods, MN-2
484. Koochiching, MN-3
485. Lake, MN-4
486. Wilkin, MN-5
487. Hubbard, MN-6
488. Chippewa, MN-7
489. Lac qui Parle, MN-8
490. Pipestone, MN-9
491. Le Sueur, MN-10
492. Goodhue, MN-11
493. Tunica, MS-1
494. Benton, MS-2
495. Bolivar, MS-3
496. Yalobusha, MS-4
497. Washington, MS-5
498. Montgomery, MS-6
499. Leake, MS-7
500. Claiborne, MS-8
501. Copiah, MS-9
502. Smith, MS-10
503. Lamar, MS-11
504. Atchison, MO-1
505. Harrison, MO-2
506. Schuyler, MO-3
507. De Kalb, MO-4
508. Linn, MO-5
509. Marion, MO-6
510. Saline, MO-7
511. Callaway, MO-8
512. Bates, MO-9
513. Benton, MO-10
514. Moniteau, MO-11
515. Maries, MO-12
516. Washington, MO-13
517. Barton, MO-14
518. Stone, MO-15
519. Laclede, MO-16
520. Shannon, MO-17
521. Perry, MO-18
522. Stoddard, MO-19
523. Lincoln, MT-1
524. Toole, MT-2
525. Phillips, MT-3
526. Daniels, MT-4
527. Mineral, MT-5
528. Deer Lodge, MT-6
529. Fergus, MT-7
530. Beaverhead, MT-8
531. Carbon, MT-9
532. Prairie, MT-10
533. Sioux, NE-1
534. Cherry, NE-2
535. Knox, NE-3
536. Grant, NE-4
537. Boone, NE-5
538. Keith, NE-6
539. Hall, NE-7
540. Chase, NE-8
541. Adams, NE-9
542. Cass, NE-10
543. Humboldt, NV-1
544. Lander, NV-2
545. Storey, NV-3
546. Mineral, NV-4
547. White Pine, NV-5
548. Coos, NH-1
549. Carroll, NH-2
550. Hunterdon, NJ-1
551. Ocean, NJ-2
552. Sussex, NJ-3
553. San Juan, NM-1
554. Colfax, NM-2
555. Catron, NM-3
556. Santa Fe, NM-4
557. Grant, NM-5
558. Lincoln, NM-6
559. Jefferson, NY-1
560. Franklin, NY-2
561. Chautauqua, NY-3
562. Yates, NY-4
563. Otsego, NY-5
564. Columbia, NY-6
565. Cherokee, NC-1
566. Yancey, NC-2
567. Ashe, NC-3
568. Henderson, NC-4
569. Anson, NC-5
570. Chatham, NC-6
571. Rockingham, NC-7
572. Northampton, NC-8
573. Camden, NC-9
574. Harnett, NC-10
575. Hoke, NC-11
576. Sampson, NC-12
577. Greene, NC-13
578. Pitt, NC-14
579. Cabarrus, NC-15
580. Divide, ND-1
581. Bottineau, ND-2
582. Barnes, ND-3
583. McKenzie, ND-4
584. Kidder, ND-5
585. Williams, OH-1
586. Sandusky, OH-2
587. Ashtabula, OH-3
588. Mercer, OH-4
589. Hancock, OH-5
590. Morrow, OH-6
591. Tuscarawas, OH-7
592. Clinton, OH-8
593. Ross, OH-9
594. Perry, OH-10
595. Columbiana, OH-11
596. Cimarron, OK-1
597. Harper, OK-2
598. Grant, OK-3
599. Nowata, OK-4
600. Roger Mills, OK-5
601. Seminole, OK-6
602. Beckham, OK-7
603. Jackson, OK-8
604. Garvin, OK-9
605. Haskell, OK-10
606. Clatsop, OR-1
607. Hood River, OR-2
608. Umatilla, OR-3
609. Lincoln, OR-4
610. Coos, OR-5
611. Crook, OR-6
612. Crawford, PA-1
613. McKean, PA-2
614. Potter, PA-3
615. Bradford, PA-4
616. Wayne, PA-5
617. Lawrence, PA-6
618. Jefferson, PA-7
619. Union, PA-8
620. Greene, PA-9
621. Bedford, PA-10
622. Huntingdon, PA-11
623. Lebanon, PA-12
624. Newport, RI-1
625. Oconee, SC-1

Appendix 1.3 List of MSAs and RSAs

(Continued)

626. Laurens, SC-2
627. Cherokee, SC-3
628. Chesterfield, SC-4
629. Georgetown, SC-5
630. Clarendon, SC-6
631. Calhoun, SC-7
632. Hampton, SC-8
633. Lancaster, SC-9
634. Harding, SD-1
635. Corson, SD-2
636. McPherson, SD-3
637. Marshall, SD-4
638. Custer, SD-5
639. Haakon, SD-6
640. Sully, SD-7
641. Kingsbury, SD-8
642. Hanson, SD-9
643. Lake, TN-1
644. Cannon, TN-2
645. Macon, TN-3
646. Hamblen, TN-4
647. Fayette, TN-5
648. Giles, TN-6
649. Bledsoe, TN-7
650. Johnson, TN-8
651. Maury, TN-9
652. Dallam, TX-1
653. Hansford, TX-2
654. Parmer, TX-3
655. Briscoe, TX-4
656. Hardeman, TX-5
657. Jack, TX-6
658. Fannin, TX-7
659. Gaines, TX-8
660. Runnels, TX-9
661. Navarro, TX-10
662. Cherokee, TX-11
663. Hudspeth, TX-12
664. Reeves, TX-13
665. Loving, TX-14
666. Concho, TX-15
667. Burleson, TX-16
668. Newton, TX-17
669. Edwards, TX-18
670. Atascosa, TX-19
671. Wilson, TX-20
672. Chambers, TX-21
673. Box Elder, UT-1
674. Morgan, UT-2
675. Juab, UT-3
676. Beaver, UT-4
677. Carbon, UT-5
678. Piute, UT-6
679. Franklin, VT-1
680. Addison, VT-2
681. Lee, VA-1
682. Tazewell, VA-2
683. Giles, VA-3
684. Bedford, VA-4
685. Bath, VA-5
686. Highland, VA-6
687. Buckingham, VA-7
688. Amelia, VA-8
689. Greensville, VA-9
690. Frederick, VA-10
691. Madison, VA-11
692. Caroline, VA-12
693. Clallam, WA-1
694. Okanogan, WA-2
695. Ferry, WA-3
696. Grays Harbor, WA-4
697. Kittitas, WA-5
698. Pacific, WA-6
699. Skamania, WA-7
700. Whitman, WA-8
701. Mason, WV-1
702. Wetzel, WV-2
703. Monongalia, WV-3
704. Grant, WV-4
705. Tucker, WV-5
706. Lincoln, WV-6
707. Raleigh, WV-7
708. Burnett, WI-1
709. Bayfield, WI-2
710. Vilas, WI-3
711. Marinette, WI-4
712. Pierce, WI-5
713. Trempealeau, WI-6
714. Wood, WI-7
715. Vernon, WI-8
716. Columbia, WI-9
717. Door, WI-10
718. Park, WY-1
719. Sheridan, WY-2
720. Lincoln, WY-3
721. Niobrara, WY-4
722. Converse, WY-5
723. Rincon, PR-1
724. Adjuntas, PR-2
725. Ciales, PR-3
726. Aibonito, PR-4
727. Ceiba, PR-5
728. Culebra-7
729. Vieques, PR-6
730. St. Thomas, VI-1
731. St. Croix, VI-2
732. Guam
733. American Samoa
734. N. Marianas

Chapter

2

Elements of Cellular Mobile Radio System Design

2.1 General Description of the Problem

Based on the concept of efficient spectrum utilization, the cellular mobile radio system design can be broken down into many elements, and each element can be analyzed and related to the others. The major elements are (1) the concept of frequency reuse channels, (2) the co-channel interference reduction factor, (3) the desired carrier-to-interference ratio, (4) the handoff mechanism, and (5) cell splitting. The purpose of this chapter is to introduce a simple methodology which will enable us to better understand how each element affects a cellular mobile radio system.

Since the limitation in the system is the frequency resource, the challenge is to serve the greatest number of customers with a specified system quality. We may ask ourselves three questions.

1. How many customers can we serve in a busy hour?
2. How many subscribers can we take into our system?
3. How many frequency channels do we need?

2.1.1 Maximum number of calls per hour per cell

To calculate the predicted number of calls per hour per cell Q in each cell, we have to know the size of the cell and the traffic conditions in the cell. The calls per hour per cell is based on how small the theoretical cell size can be. The control of the coverage of small cells is based on technological development.

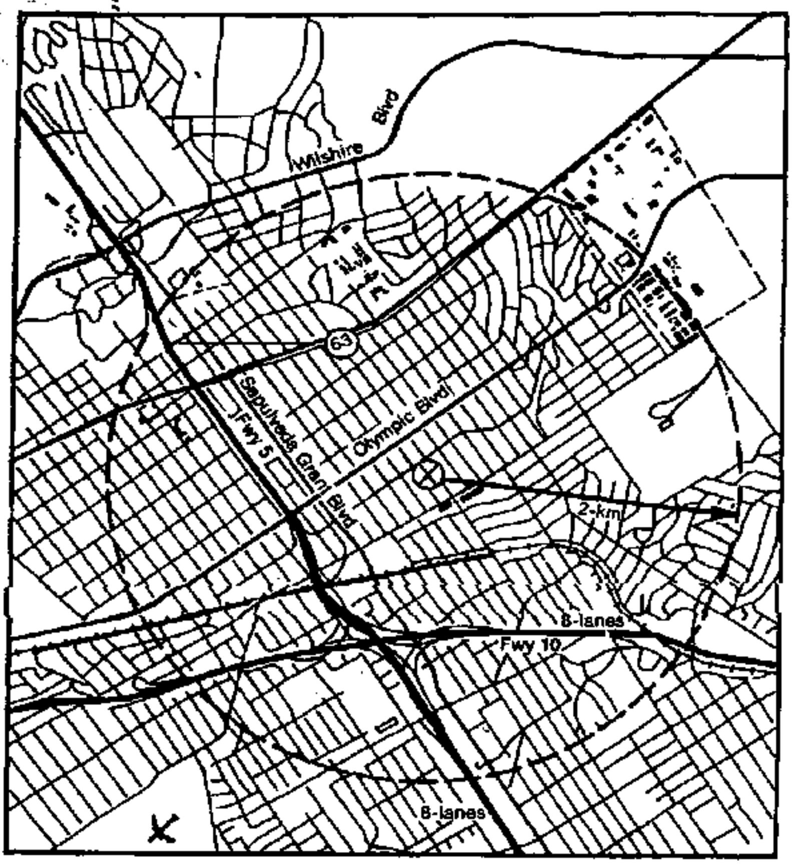


Figure 2.1 To establish the traffic capacity from a geographic map (west Los Angeles).

We assume that the cell can be reduced to a 2-km cell, which means a cell of 2-km radius. A 2-km cell in some areas may cover many highways, and in other areas a 2-km cell may only cover a few highways.

Let a busy traffic area of 12 km radius fit seven 2-km cells. The heaviest traffic cell may cover 4 freeways and 10 heavy traffic streets, as shown in Fig. 2.1. A total length of 64 km of 2 eight-lane freeways, 48 km of 2 six-lane freeways, and 588 km of 43 four-lane roads, including the 10 major roads, are obtained from Fig. 2.1. Assume that the average spacing between cars is 10 m during busy periods. We can determine that the total number of cars is about 70,000. If one-half the cars have car phones, and among them eight-tenths will make a call (η_c = 0.8) during the busy hour, there are 28,000 calls per hour, based on an average of one call per car if that car phone is used.

The maximum predicted number of calls per hour per a 2-km cell Q is derived from the above scenario. It may be an unrealistic case. However, it demonstrates how we can calculate Q for different scenarios and apply this method to finding the different Q in different geographic areas.

2.1.2 Maximum number of frequency channels per cell

The maximum number of frequency channels per cell N is closely related to an average calling time in the system. The standard user's calling habits may change as a result of the charging rate of the system and the general income profile of the users. If an average calling time T is 1.76 min and the maximum calls per hour per cell Q_i is obtained from Sec. 2.1.1, then the offered load can be derived as

$$A = \frac{Q_i T}{60} \quad \text{erlangs} \tag{2.1-1}$$

Assume that the blocking probability is given, then we can easily find the required number of radios in each cell.[1]

Example 2.1 Let the maximum calls per hour Q_i in one cell be 3000 and an average calling time T be 1.76 min. The blocking probability B is 2 percent. Then we may use Q from Eq. (2.1-1) to find the offered load A.

$$A = \frac{3000 \times 1.76}{60} = 88$$

With the blocking probability B = 2 percent, the maximum number of channels can be found from Appendix 1.1 as N = 100.

Example 2.2 If we let Q_i = 28,000 calls per cell per hour, based on one scenaro shown in Sec. 2.1.1, B = 2 percent, and T = 1.76 min, how many radio channels are needed? The offered load A is obtained as

$$A = \frac{28{,}000 \times 1.76}{60} = 821$$

Inserting the above known figures into the table of Appendix 1.1, we find that N = 820 channels per cell.

Example 2.3 If there are 50 channels in a cell to handle all the calls and the average is 100 s per call, how many calls can be handled in this cell with a blocking probability of 2 percent? Since N = 50 and B = 2 percent, the offered load can be found from Appendix 1.1 as

$$A = 40.3$$

The number of calls per hour in a cell is

$$Q_i = \frac{40.3 \times 3600}{100} = 1451 \text{ calls per hour}$$

Example 2.4 If the maximum number of calls per hour per cell is 1451 and there is a seven-cell reuse pattern* in the system ($K = 7$), and assuming that $B = 2$ percent and $T = 100$ s as in Example 2.3, then $N = 50$ as indicated. The total number of required channels for a $K = 7$ reuse system is

$$N_t = 50 \times 7 = 350 \text{ radios}$$

If a large area is covered by 28 cells, $K_t = 28$; the total number of customers $M_t = \Sigma_{i=1}^{K_t} M_i$ in the system increases. Therefore, we may assume that the number of subscribers per cell M_i is somehow related to the percentage of car phones used in the busy hours (η_c) and the number of calls per hour per cell Q_i as

$$M_i = f(Q_i, \eta_c) \tag{2.1-2}$$

where the value Q_i is a function of the blocking probability B, the average calling time T, and the number of channels N.

$$Q_i = f(B, T, N) \tag{2.1-3}$$

If the $K = 7$ frequency reuse pattern is used, the total number of required channels in the system is $N_t = 7 \times N$. We must realize that it is the maximum number of calls per cell Q_i that determines the total required channels N_t, not the total number of subscribers M_t. In this case ($K_t = 30$ and $K = 7$), the total number of channels N_t has been used four times in the system.

2.2 Concept of Frequency Reuse Channels

A radio channel consists of a pair of frequencies, one for each direction of transmission that is used for full-duplex operation. A particular radio channel, say F_1, used in one geographic zone to call a cell, say C_1, with a coverage radius R can be used in another cell with the same coverage radius at a distance D away.

Frequency reuse is the core concept of the cellular mobile radio system. In this frequency reuse system, users in different geographic locations (different cells) may simultaneously use the same frequency

* Its pattern is shown in Fig. 2.3 and described in Sec. 2.2.1.

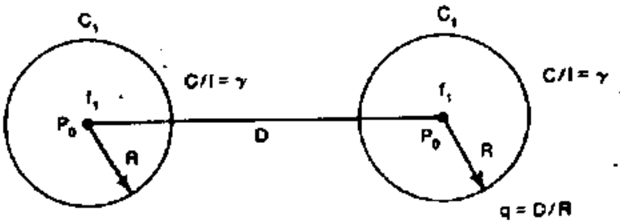


Figure 2.2 The ratio of D/R.

channel (see Fig. 2.2). The frequency reuse system can drastically increase the spectrum efficiency, but if the system is not properly designed, serious interference may occur. Interference due to the common use of the same channel is called *cochannel interference* and is our major concern in the concept of frequency reuse.

2.2.1 Frequency reuse schemes

The frequency reuse concept can be used in the time domain and the space domain. Frequency reuse in the time domain results in the occupation of the same frequency in different time slots. It is called *time-division multiplexing* (TDM). Frequency reuse in the space domain can be divided into two categories.

1. Same frequency assigned in two different geographic areas, such as AM or FM radio stations using the same frequency in different cities.
2. Same frequency repeatedly used in a same general area in one system[2]—the scheme is used in cellular systems. There are many cochannel cells in the system. The total frequency spectrum allocation is divided into K frequency reuse patterns, as illustrated in Fig. 2.3 for K = 4, 7, 12, and 19.

2.2.2 Frequency reuse distance[2,3,7,8]

The minimum distance which allows the same frequency to be reused will depend on many factors, such as the number of cochannel cells in the vicinity of the center cell, the type of geographic terrain contour, the antenna height, and the transmitted power at each cell site.

The frequency reuse distance D can be determined from

$$D = \sqrt{3K}\,R \tag{2.2-1}$$

Where K is the frequency reuse pattern shown in Fig. 2.2, then

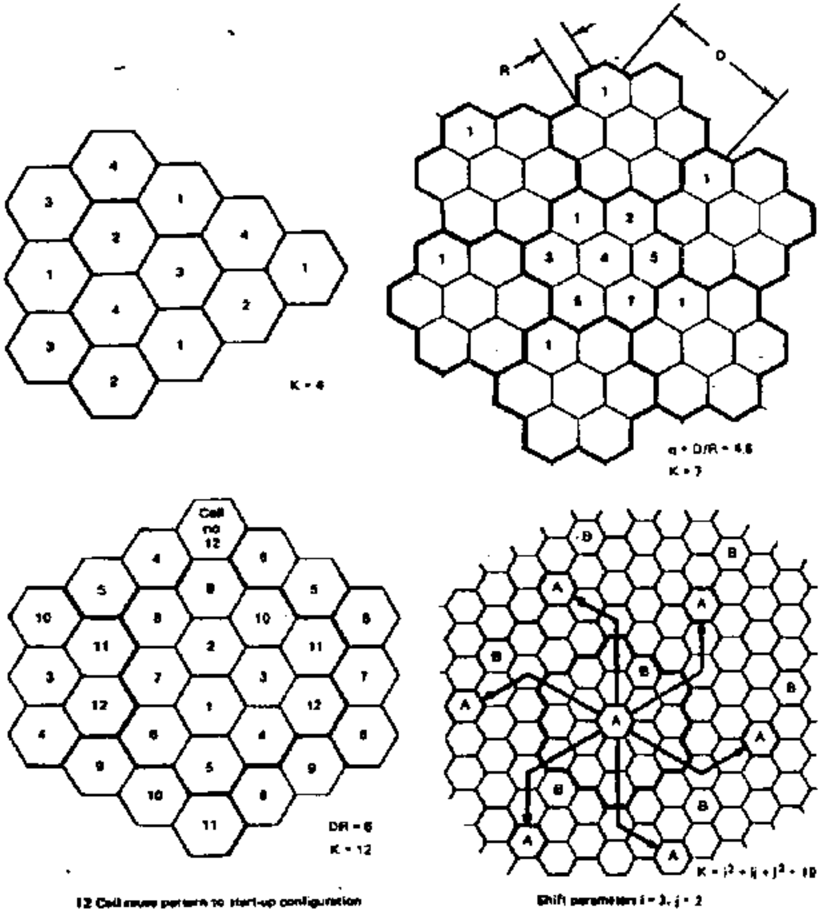


Figure 2.3 . *N*-cell reuse pattern.

$$D = \begin{cases} 3.46R & K = 4 \\ 4.6R & K = 7 \\ 6R & K = 12 \\ 7.55R & K = 19 \end{cases}$$

If all the cell sites transmit the same power, then K increases and the frequency reuse distance D increases. This increased D reduces the chance that cochannel interference may occur.

Theoretically, a large K is desired. However, the total number of allocated channels is fixed. When K is too large, the number of channels assigned to each of K cells becomes small. It is always true that if the total number of channels in K cells is divided as K increases, trunking inefficiency results. The same principle applies to spectrum inefficiency: if the total number of channels are divided into two network systems serving in the same area, spectrum inefficiency increases, as mentioned in Sec. 1.3.

Now the challenge is to obtain the smallest number K which can still meet our system performance requirements. This involves estimating cochannel interference and selecting the minimum frequency reuse distance D to reduce cochannel interference. The smallest value of K is $K = 3$, obtained by setting $i = 1$, $j = 1$ in the equation $K = i^2 + ij + j^2$ (see Fig. 2.3).

2.2.3 Number of customers in the system

When we design a system, the traffic conditions in the area during a busy hour are some of the parameters that will help determine both the sizes of different cells and the number of channels in them.

The maximum number of calls per hour per cell is driven by the traffic conditions at each particular cell. After the maximum number of frequency channels per cell has been implemented in each cell, then the maximum number of calls per hour can be taken care of in each cell. Now, take the maximum number of calls per hour in each cell Q_i and sum them over all cells. Assume that 60 percent of the car phones will be used during the busy hour, on average, one call per phone ($\eta_c = 0.6$) if that phone is used. The total allowed subscriber traffic M_t can then be obtained.

Example 2.5 During a busy hour, the number of calls per hour Q_i for each of 10 cells is 2000, 1500, 3000, 500, 1000, 1200, 1800, 2500, 2800, 900. Assume that 60 percent of the car phones will be used during this period ($\eta_c = 0.6$) and that one call is made per car phone. Summing over all Q_i gives the total Q_t

$$Q_t = \sum_{i=1}^{10} Q_i = 17{,}200 \text{ calls per hour}$$

Since $\eta_c = 0.6$, the number of customers in the system is

$$M_t = \frac{17{,}200}{0.6} = 28{,}667$$

2.3 Cochannel Interference Reduction Factor

Reusing an identical frequency channel in different cells is limited by cochannel interference between cells, and the cochannel interference can become a major problem. Here we would like to find the minimum frequency reuse distance in order to reduce this cochannel interference.

Assume that the size of all cells is roughly the same. The cell size is determined by the coverage area of the signal strength in each cell. As long as the cell size is fixed, cochannel interference is independent of the transmitted power of each cell. It means that the received threshold level at the mobile unit is adjusted to the size of the cell. Actually, cochannel interference is a function of a parameter q defined as

$$q = \frac{D}{R} \tag{2.3-1}$$

The parameter q is the cochannel interference reduction factor. When the ratio q increases, cochannel interference decreases. Furthermore, the separation D in Eq. (2.3-1) is a function of K_I and C/I,

$$D = f(K_I, C/I) \tag{2.3-2}$$

where K_I is the number of cochannel interfering cells in the first tier and C/I is the received carrier-to-interference ratio at the desired mobile receiver.[3]

$$\frac{C}{I} = \frac{C}{\sum_{k=1}^{K_I} I_k} \tag{2.3-3}$$

In a fully equipped hexagonal-shaped cellular system, there are always six cochannel interfering cells in the first tier, as shown in Fig. 2.4; that is, $K_I = 6$. The maximum number of K_I in the first tier can be shown as six (i.e., $2\pi D/D \approx 6$). Cochannel interference can be experienced both at the cell site and at mobile units in the center cell. If the interference is much greater, then the carrier-to-interference ratio C/I at the mobile units caused by the six interfering sites is (on the average) the same as the C/I received at the center cell site caused by interfering mobile units in the six cells. According to both the reciprocity theorem and the statistical summation of radio propagation, the two C/I values can be very close. Assume that the local noise is much less than the interference level and can be neglected. C/I then can be expressed, from Eq. (1.6-4), as

$$\frac{C}{I} = \frac{R^{-\gamma}}{\sum_{k=1}^{K_I} D_k^{-\gamma}} \tag{2.3-4}$$

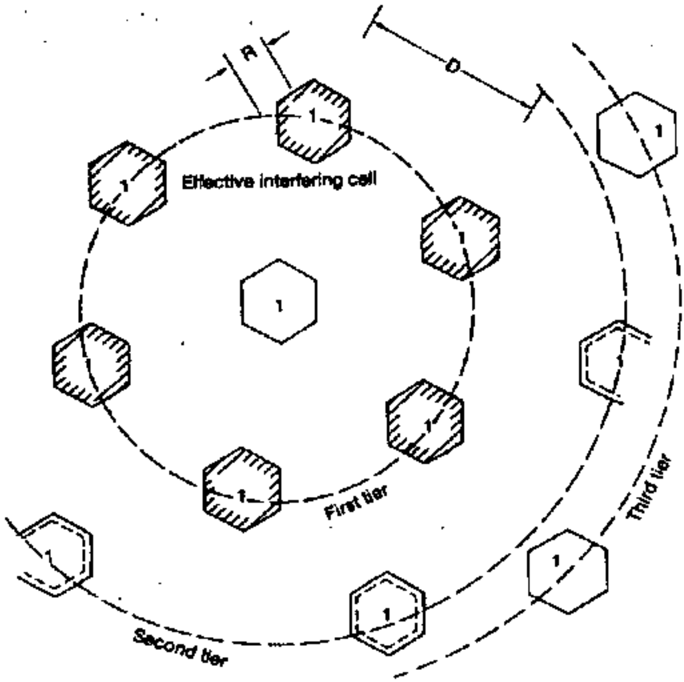


Figure 2.4 Six effective interfering cells of cell 1.

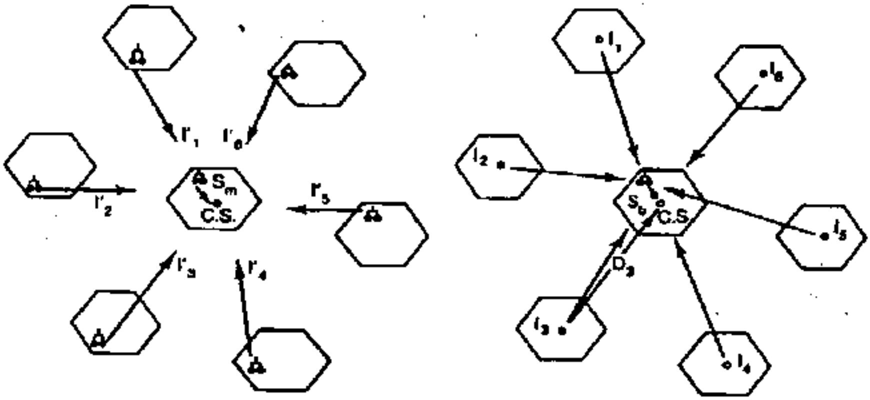
where γ is a propagation path-loss slope[5] determined by the actual terrain environment. In a mobile radio medium, γ usually is assumed to be 4 (see Sec. 1.6). K_I is the number of cochannel interfering cells and is equal to 6 in a fully developed system, as shown in Fig. 2.4. The six cochannel interfering cells in the second tier cause weaker interference than those in the first tier (see Example 2.6 at the end of Sec. 2.4.1).

Therefore, the cochannel interference from the second tier of interfering cells is negligible. Substituting Eq. (2.3-1) into Eq. (2.3-4) yields

$$\frac{C}{I} = \frac{1}{\sum_{k=1}^{K_I} \left(\frac{D_k}{R}\right)^{-\gamma}} = \frac{1}{\sum_{k=1}^{K_I} (q_k)^{-\gamma}} \tag{2.3-5}$$

where q_k is the cochannel interference reduction factor with kth cochannel interfering cell

$$q_k = \frac{D_k}{R} \tag{2.3-6}$$



(a) (b)

Figure 2.5 Cochannel interference from six interferers. (*a*) Receiving at the cell site; (*b*) receiving at the mobile unit.

2.4 Desired C/I from a Normal Case in an Omnidirectional Antenna System

2.4.1 Analytic solution

There are two cases to be considered: (1) the signal and cochannel interference received by the mobile unit and (2) the signal and cochannel interference received by the cell site. Both cases are shown in Fig. 2.5. N_m and N_b are the local noises at the mobile unit and the cell site, respectively. Usually N_m and N_b are small and can be neglected as compared with the interference level. The effect of the cochannel interference on spectrum efficiency systems will appear in Sec. 13.4. As long as the received carrier-to-interference ratios at both the mobile unit and the cell site are the same, the system is called a *balanced system*. In a balanced system, we can choose either one of the two cases to analyze the system requirement; the results from one case are the same for the others.

Assume that all D_k are the same for simplicity, as shown in Fig. 2.4; then $D = D_k$, and $q = q_k$, and

$$\frac{C}{I} = \frac{R^{-\gamma}}{6D^{-\gamma}} = \frac{q^{\gamma}}{6} \tag{2.4-1}$$

Thus

$$q^{\gamma} = 6\,\frac{C}{I} \tag{2.4-2}$$

and

$$q = \left(6 \frac{C}{I}\right)^{1/\gamma} \qquad (2.4\text{-}3)$$

In Eq. (2.4-3), the value of C/I is based on the required system performance and the specified value of γ is based on the terrain environment. With given values of C/I and γ, the cochannel interference reduction factor q can be determined. Normal cellular practice is to specify C/I to be 18 dB or higher based on subjective tests and the criterion described in Sec. 1.5. Since a C/I of 18 dB is measured by the acceptance of voice quality from present cellular mobile receivers, this acceptance implies that both mobile radio multipath fading and cochannel interference become ineffective at that level. The path-loss slope γ is equal to about 4 in a mobile radio environment.[5]

$$q = D/R = (6 \times 63.1)^{1/4} = 4.41 \qquad (2.4\text{-}4)$$

The 90th percentile of the total covered area would be achieved by increasing the transmitted power at each cell; increasing the same amount of transmitted power in each cell does not affect the result of Eq. (2.4-4). This is because q is not a function of transmitted power. The computer simulation described in the next section finds the value of $q = 4.6$, which is very close to Eq. (2.4-4). The factor q can be related to the finite set of cells K in a hexagonal-shaped cellular system by

$$q = \triangleq \sqrt{3K} \qquad (2.4\text{-}5)$$

Substituting q from Eq. (2.4-4) into Eq. (2.4-5) yields

$$K = 7 \qquad (2.4\text{-}6)$$

Equation (2.4-6) indicates that a seven-cell reuse pattern* is needed for a C/I of 18 dB. The seven-cell reuse pattern is shown in Fig. 2.3.

Based on $q = D/R$, the determination of D can be reached by choosing a radius R in Eq. (2.4-4). Usually, a value of q greater than that shown in Eq. (2.4-4) would be desirable. The greater the value of q, the lower the cochannel interference. In a real environment, Eq. (2.3-5) is always true, but Eq. (2.4-1) is not. Since Eq. (2.4-4) is derived from Eq. (2.4-1), the value q may not be large enough to maintain a carrier-to-interference ratio of 18 dB. This is particularly true in the worst case, as shown in Chap. 6.

* In this seven-cell reuse pattern, the total allocated frequency band is divided into seven subsets. Each particular subset of frequency channels is assigned to one of seven cells.

Example 2.6 Compare interference from the first tier of six interferers with that from twelve interferers (first and second tiers) (see Fig. 2.4).

From the first tier,

$$\frac{C}{I} = \frac{C}{\sum_{i=1}^{6} I_i} = \frac{R_1^{-4}}{6D_1^{-4}} = \frac{a_1^4}{6} \tag{E2.6-1}$$

From the first and second tiers,

$$\frac{C}{I} = \frac{C}{\sum_{i=1}^{6} (I_{1i} + I_{2i})} = \frac{1}{6(a_1^{-4} + a_2^{-4})} \tag{E2.6-2}$$

Since we have found $a_1 = 4.6$, then from the second tier, $a_2 = D_2/R_1 \approx 2D_1/R_1 = 2a_1 = 9.2$. Substituting a_1 and a_2 into Eqs. (E2.6-1) and (E2.6-2), respectively, yields

$$\left(\frac{C}{I}\right)_{\text{1st tier}} = 18.72 \text{ dB}$$

$$\left(\frac{C}{I}\right)_{\text{1st and 2nd tiers}} = 18.46 \text{ dB}$$

We realize that a negligible amount of interference is contributed by the six interferers from the second tier.

2.4.2 Solution obtained from simulation

The required cochannel reduction factor q can be obtained from the simulation also. Let one main cell site and all six possible cochannel interferers be deployed in a pattern, as shown in Fig. 2.4. The distance D from the center cell to the cochannel interferers in the simulation is a variable. $D = 2R$ can be used initially and incremented every $0.5R$ as $D = 2R$, $2.5R$, $3R$. For every particular value of D, a set of simulation data is generated.

First, the location of each mobile unit in its own cell is randomly generated by a random generator. Then the distance D_k from each of the six interfering mobile units to the center cell site (assuming $K_I = 6$) is obtained. The desired mobile signal as well as six interference levels received at the center cell site would be randomly generated following the mobile radio propagation path-loss rule, which is 40 dB/dec, along with a log-normal standard deviation of 8 dB at its mean value. Summing up all the data from six simulated interferences,

$$I = \sum_{k=1}^{K_I=6} I_k$$

and dividing it by the simulated main carrier, value C becomes C/I.

This C/I is for a particular D, the distance between the center cell site and the cochannel cell sites (cochannel interferers). Repeat this process, say 1000 times, for each particular value of D, based on the criterion stated in Sec. 1.5 (that 75 percent of the users say voice quality is "good" or "excellent" in 90 percent of the total covered area). Then from 75 percent of the users' opinion, $C/I = 18$ dB needs to be achieved[4] with a proper value of D. Assuming that mobile unit locations are chosen randomly and uniformly, then 90 percent of the area corresponds to 900 out of 1000 mobile unit locations.

To find a proper value for D, each mobile unit location associates with its received C/I. Some C/I values are high and some are low. This means that the lowest 100 values of C/I should be discarded. The main C/I value should be derived from the remaining 900 C/I values. This associates a particular C/I for a particular separation D. Repeating this process for different values of D, the corresponding mean C/I values are found. The C/I versus D curve can be plotted, depicting $C/I = 18$ dB as corresponding to $D = 4.6R$, as illustrated in the Bell Lab publication.[4] Then

$$q = \frac{D}{R} = 4.6 \tag{2.4-7}$$

Comparing the values of q obtained from an analytic solution shown in Eq. (2.4-4) and q obtained from a simulation solution shown in Eq. (2.4-7), the results are surprisingly close.

Although a simulation (statistical) approach deals with a real-world situation, it does not provide a clear physical picture. The two agreeable solutions illustrated in this section prove that the simple analytic method is implementable in a cellular system based on hexagonal cells.

2.5 Handoff Mechanism

The handoff is the process mentioned in Sec. 1.7. It is a unique feature that allows cellular systems to operate as effectively as demonstrated in actual use. To clearly describe the handoff concept, it is easy to use a one-dimensional illustration as shown in Fig. 2.6, although a real two-dimensional cellular configuration would cover an area with cells. The handoff concept as applied to a one-dimensional case will also apply to two-dimensional cases.

Two cochannel cells using the frequency F_1 separated by a distance D are shown in Fig. 2.6a. The radius R and the distance D are governed by the value of q. Now we have to fill in with other frequency

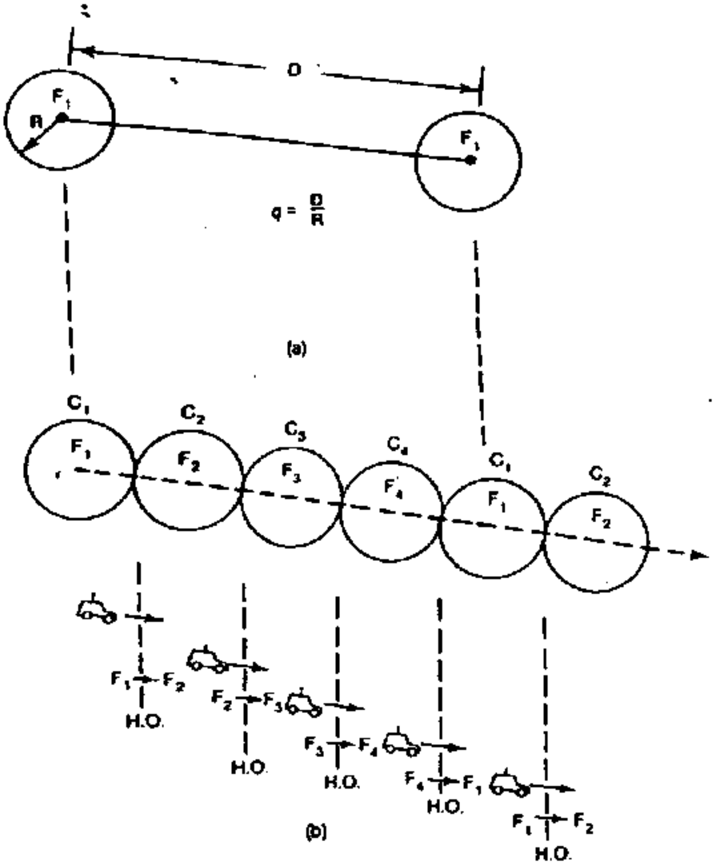


Figure 2.6 Handoff mechanism. (*a*) Cochannel interference reduction ratio q. (*b*) Fill-in frequencies.

channels such as F_2, F_3, and F_4 between two cochannel cells in order to provide a communication system in the whole area.

The fill-in frequencies F_2, F_3, and F_4 are also assigned to their corresponding cells C_2, C_3, and C_4 (see Fig. 2.6*b*) according to the same value of q.

Suppose a mobile unit is starting a call in cell C_1 and then moves to C_2. The call can be dropped and reinitiated in the frequency channel from F_1 to F_2 while the mobile unit moves from cell C_1 to cell C_2. This process of changing frequencies can be done automatically by the system without the user's intervention. This process of handoff is carried on in the cellular system.

The handoff processing scheme is an important task for any successful mobile system. How does one make any one of the necessary handoffs successful? How does one reduce all unnecessary handoffs in the system? How is the individual cell traffic capacity controlled by altering the handoff algorithm? All these questions will be answered in Chap. 9.

2.6 Cell Splitting

2.6.1 Why splitting?

The motivation behind implementing a cellular mobile system is to improve the utilization of spectrum efficiency.[5,9] The frequency reuse scheme is one concept, and cell splitting is another concept. When traffic density starts to build up and the frequency channels F_i in each cell C_i cannot provide enough mobile calls, the original cell can be split into smaller cells. Usually the new radius is one-half the original radius (see Fig. 2.7). There are two ways of splitting: In Fig. 2.7*a*, the original cell site is not used, while in Fig. 2.7*b*, it is.

$$\text{New cell radius} = \frac{\text{old cell radius}}{2} \tag{2.6-1}$$

Then based on Eq. (2.6-1), the following equation is true.

$$\text{New cell area} = \frac{\text{old cell area}}{4} \tag{2.6-2}$$

Let each new cell carry the same maximum traffic load of the old cell; then, in theory,

$$\frac{\text{New traffic load}}{\text{Unit area}} = 4 \times \frac{\text{traffic load}}{\text{unit area}}$$

2.6.2 How splitting?

There are two kinds of cell-splitting techniques:

1. *Permanent splitting.* The installation of every new split cell has to be planned ahead of time; the number of channels, the transmitted power, the assigned frequencies, the choosing of the cell-site selection, and the traffic load consideration should all be considered. When ready, the actual service cut-over should be set at the lowest traffic point, usually at midnight on a weekend. Hopefully, only a few calls will be dropped because of this cut-over, assuming that the downtime of the system is within 2 h.

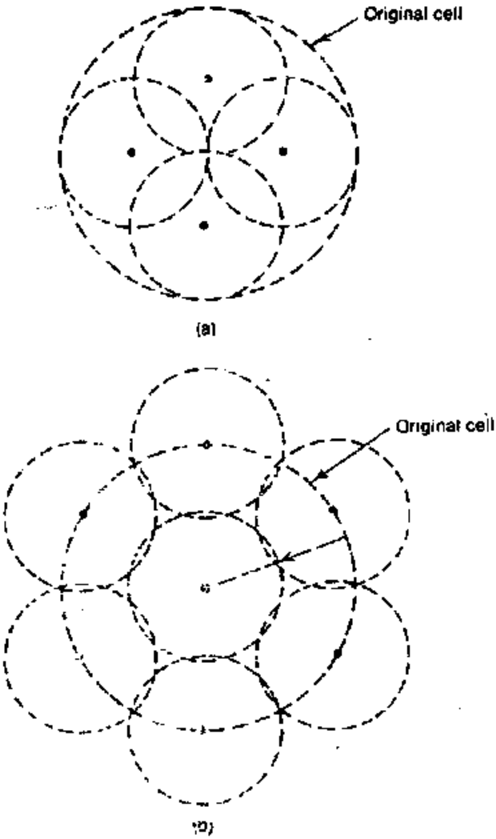


Figure 2.7 Cell splitting.

2. *Dynamic splitting.* This scheme is based on utilizing the allocated spectrum efficiency in real time. The algorithm for dynamically splitting cell sites is a tedious job since we cannot afford to have one single cell unused during cell splitting at heavy traffic hours. Section 10.4.2 will discuss this topic in depth.

2.7 Consideration of the Components of Cellular Systems

The elements of cellular mobile radio system design have been mentioned in the previous sections. Here we must also consider the components of cellular systems, such as mobile radios, antennas, cell-site

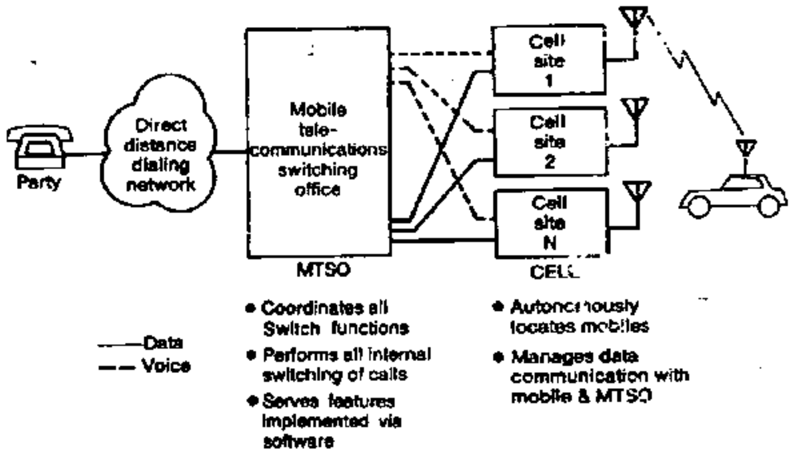


Figure 2.8 A general view of cellular telecommunications systems.

controller, and MTSO. They would affect our system design if we do not choose the right one. The general view of the cellular system is shown in Fig. 2.8. Even though the EIA (Electronic Industries Association) and the FCC have specified standards for radio equipment at the cell sites and the mobile sites, we still need to be concerned about that equipment. The issues affecting choice of antennas, switching equipment, and data links are briefly described here.

2.7.1 Antennas

Antenna pattern, antenna gain, antenna tilting, and antenna height[6] all affect the cellular system design. The antenna pattern can be omnidirectional, directional, or any shape in both the vertical and the horizon planes. Antenna gain compensates for the transmitted power. Different antenna patterns and antenna gains at the cell site and at the mobile units would affect the system performance and so must be considered in the system design.

The antenna patterns seen in cellular systems are different from the patterns seen in free space. If a mobile unit travels around a cell site in areas with many buildings, the omnidirectional antenna will not duplicate the omnipattern. In addition, if the front-to-back ratio of a directional antenna is found to be 20 dB in free space, it will be only 10 dB at the cell site. An explanation for these phenomena is given in Chapter 5.

Antenna tilting can reduce the interference to the neighboring cells and enhance the weak spots in the cell. Also the height of the cell-site antenna can affect the area and shape of the coverage in the system. The effect of antenna height will be described in Chap. 4.

2.7.2 Switching equipment

The capacity of switching equipment in cellular systems is not based on the number of switch ports but on the capacity of the processor associated with the switches. In a big cellular system, this processor should be large. Also, because cellular systems are unlike other systems, it is important to consider when the switching equipment would reach the maximum capacity.

The service life of the switching equipment is not determined by the life cycle of the equipment but by how long it takes to reach its full capacity. If the switching equipment is designed in modules, or as distributed switches, more modules can be added to increase the capacity of the equipment. For decentralized systems digital switches may be more suitable. The future trend seems to be the utilization of system handoff. This means that switching equipment can link to other switching equipment so that a call can be carried from one system to another system without the call being dropped. We will discuss these issues in Chap. 11.

2.7.3 Data links

The data links are shown in Fig. 2.8. Although they are not directly affected by the cellular system, they are important in the [illegible]. Each data link can carry multiple channel data (10 kbps data transmitted per channel) from the cell site to the MTSO. This fast-speed data transmission cannot be passed through a regular telephone line. Therefore, data bank devices are needed. They can be multiplexed, many-data channels passing through a wideband T-carrier wire line or going through a microwave radio link where the frequency is much higher than 850 MHz.

Leasing T1-carrier wire lines through telephone companies can be costly. Although the use of microwaves may be a long-term money saver, the availability of the microwave link has to be considered and is described in Chap. 12. The arrangement of data links will be described in Chap. 11.

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Chapter

3

Specifications of Analog Systems

In this chapter, we concentrate on U.S. analog cellular mobile specifications.[1] Also, we touch on the differences in other foreign analog cellular mobile systems.

3.1 Definitions of Terms and Functions

1. *Home mobile station (unit).* A mobile station that is subscribed in its cellular system.
2. *Land station.* A station other than a mobile station, which links to the mobile station.
3. *Control channel.* A channel used for the transmission of digital control information from a land station to a mobile station, or vice versa.
4. *Forward control channel* (FDCC). A control channel used from a land station to a mobile station.
5. *Reverse control channel* (RECC). A control channel used from a mobile station to a land station.
6. *Forward voice channel* (FVC). A voice channel used from a land station to a mobile unit.
7. *Reverse voice channel* (RVC). A voice channel used from a mobile station to a land station.
8. *Set-up channels.* A number of designated control channels.

9. *Access channel.* A control channel used by a mobile station to access a system and obtain service. The access channel always accesses from the mobile station to the cell site.

10. *Paging channel.* The act of seeking a mobile station when an incoming call from the land line has been placed to it.

11. *Digital color code* (DC). A digital signal transmitted by a forward control channel to detect capture of an interfering mobile station. There are four codes (See Sec. 3.2.8.)

12. *Flash request.* A message sent on a voice channel from a mobile station to a land station indicating a user's desire to invoke special processing, such as an emergency.

13. *Signaling tone.* A 10-kHz tone transmitted by the mobile station on a voice channel. It serves several functions.

14. *Handoff.* The act of transferring a mobile station from one voice channel to another voice channel. There are two kinds of handoffs:
    a. Interhandoff, from one cell to another cell
    b. Intrahandoff, within a cell

15. *Numeric information.* Used to describe the operation of the mobile station.

Numeric indicators

MIN	mobile identification number
MIN1	24 bits that correspond to the seven-digit directory number assigned to the mobile station
MIN2	10 bits that correspond to the three-digit area code
BIS	Identifies whether a mobile station must check an idle-to-busy transition on a reverse control channel when accessing a system. In a forward control-channel busy-idle bit inserts in every 10-bit interval of a transmitted bit stream.
CCLIST	scanned by a mobile station on a list of control channels
CMAX	maximum number of control channels to be scanned by the mobile station (up to 21 channels)
MAXBUSY	maximum number of busy occurrences allowed on a reversed control channel
MAXSZTR	maximum number of seizure attempts allowed on a reversed control channel
NBUSY	number of times a mobile station attempts to seize a reverse control channel and finds it busy
NSZTR	number of times a mobile station attempts to seize a reverse control channel and fails
PL	mobile station RF power level

SCC a digital number that is stored and used to identify which SAT (see item 20 below) frequency a mobile station should be received on

16. *Paging.* The act of seeking a mobile station when an incoming call from the land station has been placed to it.
17. *Paging channel.* A forward control channel which is used to page mobile stations and send orders.
18. *Registration.* The procedure by which a mobile station identifies itself to a land station as being active.
19. *Roamer.* A mobile station which operates in a cellular system other than the one from which service is subscribed.
20. *Supervisory audio tone* (SAT). One of three tones in the 6-kHz region; there is one SAT frequency for each land station. In certain circumstances, there is one SAT frequency for each sector of each land station.
21. *System identification* (SID). A digital identification uniquely associated with a cellular system.
22. *Electronic serial number* (ESN). Each mobile station has an ESN assigned by the manufacturer.
23. *Group identification.* A subset of the most significant bits of SID that is used to identify a group of cellular systems, such as NYNEX systems, PacTel systems, Southwestern Bell systems.
24. *Channel spacing.* 30 kHz per one-way channel. As an example, channel 1 is 825.030 MHz (mobile transmit) and 870.030 MHz (land transmit). Additional spectrum allocation of 10 MHz for the cellular industry changes the channel numbering order.

3.2 Specification of Mobile Station (Unit) in the United States[1-3]

3.2.1 Power

Let P_0 be the specified power and f_0 be the specified frequency channel. P and f are the operating power and frequency, respectively.

Power level (carrier-off condition) requires $P < -60$ dBm in 2 ms

Power level (carrier-on-condition) within 3 dB of specified power(P_0) within 2 ms

Power level (off-frequency condition), if $|f - f_c| > 1$ kHz, do not transmit; then $P < -60$ dBm

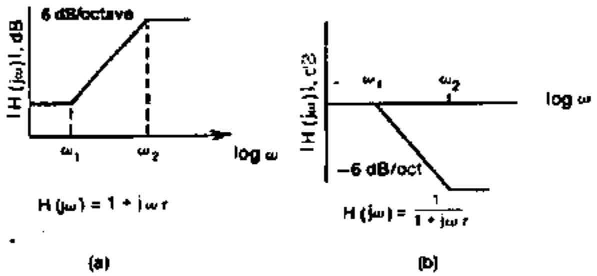


Figure 3.1 Preemphasis/deemphasis response. (*a*) Preemphasis response $\omega_1 = 1/\tau$, $\omega_2 = 2\pi f_2$. (*b*) Deemphasis response $\omega_1 = 1/\tau$, $\omega_2 = 2\pi f_2$.

Power transmitted levels are maximum effective radiated power (ERP) with respect to a half-wave dipole

Mobile stations have three station class marks:

Power class	P, power level = 0	Tolerance
I	6 dBW (4.0 W)	(8 dBW ≤ P ≤ 2 dBW)
II	2 dBW (1.6 W)	(4 dBW ≤ P ≤ −2 dBW)
III	−2 dBW (0.6 W)	(0 dBW ≤ P ≤ −6 dBW)

Each mobile station power class I has eight full power levels (0 to 7), with power level 0 being the highest. Each level has a 4-dB drop. The total power control range for power class I (mobile) is 28 dB. The names CMAC and VMAC indicate the maximum control and maximum voice attenuation codes, respectively. For all three mobile station power classes, power level 7 is −22 dBW (or 8 dBm or 6.3 mW).

3.2.2 Modulation

1. *Compressor/expander* (*compander*). A 2:1 syllabic compander is used. Every 2-dB change in input level converts (compresses) to 1 dB at output (at the transmitted side). Then reverse the two numbers (expand) at the received side. It serves two purposes:
   a. To confine the energy in the channel bandwidth
   b. To generate a quieting effect during a speech pulse
2. *Preemphasis/deemphasis* (see Fig. 3.1). The preemphasis network and its response are shown in Fig. 3.1. The improvement factor ρ_{FM} is[4]

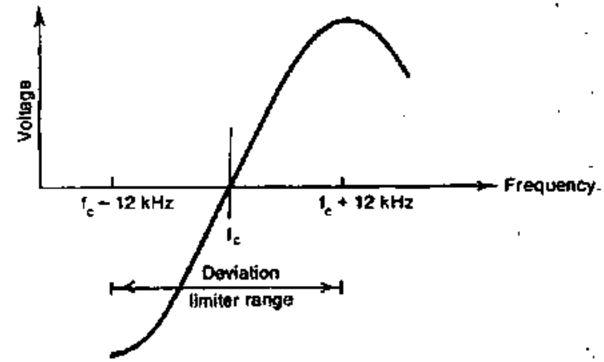


Figure 3.2 Deviation limiter characteristics.

$$\rho_{FM} = \frac{(f_2/f_1)^3}{3[f_2/f_1 - \tan^{-1}(f_2/f_1)]}$$

For $f_2/f_1 < 2$, ρ_{FM} approaches 1.
For wideband, $f_2 \gg f_1$. Thus

$$\rho_{FM} = \frac{(f_2/f_1)^2}{3}$$

For $f_2 = 3$ kHz and $f_1 = 300$ Hz, the improvement factor ρ_{FM} is

$$\rho_{FM} = 10 \log \frac{100}{3} = 15.23 \text{ dB}$$

3. *Deviation limiter.* A mobile station must limit the instantaneous frequency deviation to ±12 kHz. The deviation limiter of the frequency-to-voltage characteristic is shown in Fig. 3.2.
4. *Wideband data signal.* A NRZ (non-return-to-zero) binary data stream is encoded to a Manchester (biphase) code, as shown in Fig. 3.3. It modulates to a ±8-kHz binary FSK with a transmission rate of 10 kbps. The advantage of using a Manchester code in a voice channel is that the energy of this code is concentrated at the transmisson rate of 10 kHz. Therefore, a burst of signals transmitted over the voice channel can be detected. The Manchester code is applied to both control channels and voice channels.

3.2.3 Limitation on emission

It is very important that each mobile station have a limit on its emission. An RF signal emitted by any receiver has to be less than some

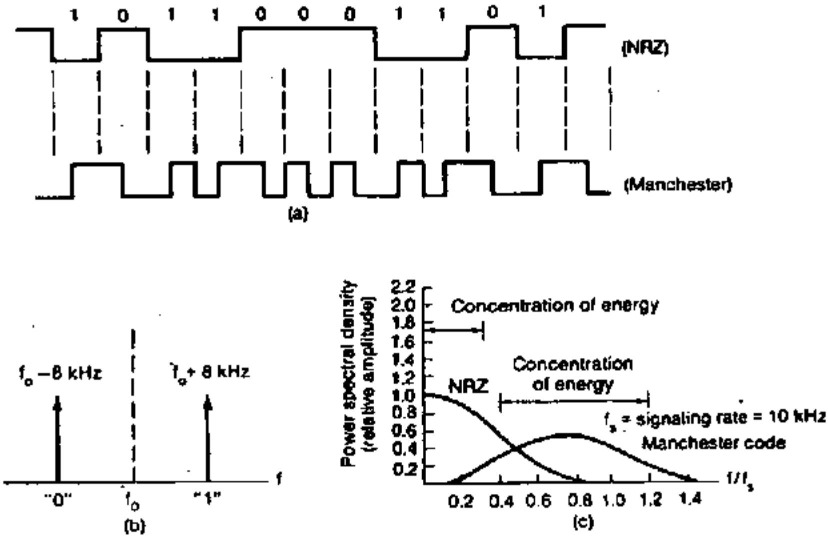
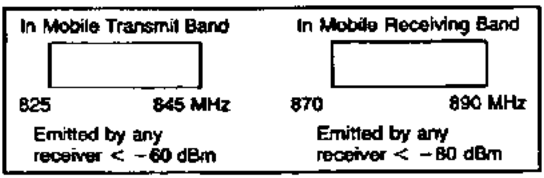


Figure 3.3 Waveforms and power spectral densities of NRZ and Manchester code. (*a*) Waveforms of NRZ and Manchester code. (*b*) Use of two frequency deviations to represent two levels. (*c*) Power spectral densities of NRZ and Manchester code.

value, which in turn depends on different frequency bands. The values are shown in the box as follows.



3.2.4 Security and identification

1. *Mobile identification number* (MIN). A binary number of 34 bits ($2^{34} \approx 1.7 \times 10^{10}$) derived from a 10-digit directory telephone number.

2. *Electronic serial number* (ESN). A 32-bit binary number that uniquely identifies a mobile unit and must be set by the factory. Attempts to change the serial number circuit should render the mobile unit *inoperative*.

The manufacturer should not overlook this requirement, and each operating system has to check that this requirement is enforced from different manufactured units. This number will be used in the system for security purposes.

An amount of revenue can be lost to the system operation if the manufacturer fails to implement this requirement in the mobile unit and a false ESN can be used in place easily.

3. *First paging channel* (FIRSTCHP). An 11-bit system which identifies the channel number of the first paging channel when the mobile station is "home." It is stored in the mobile unit.

4. *Home system identification* (SID). Fifteen-bit system used to identify the home station. The least significant bit is 1 for a Block A system, otherwise 0 for a Block B system.

5. *Preferred system selection.* Provided as a means for selecting the preferred system as either system A or system B within a mobile station.

3.2.5 Supervision

SAT (supervisory audio tone)

1. *SAT function.* There are three SAT tones: 5970, 6000, and 6030 Hz. The tolerance of each tone is ±15 Hz. The features of the SAT tones are
   - *a.* Each land station is assigned to one SAT among the three listed above.
   - *b.* One SAT tone is added to each forward voice channel (FVC) by a land station. The mobile station detects, filters, and modulates on the reversed voice channel (RVC) with this same tone.
   - *c.* SAT is suspended during transmission of wideband data (a burst of signaling of 10 kbps), information, or other control features on the reverse voice channel.
   - *d.* It is not suspended when a signaling tone (10 kHz) is sent.
   - *e.* The received audio transmission must be muted if the measured SAT and SCC do not agree with each other.
2. *SAT transmission.* The tone modulation index is ⅓. It is a narrowband FM. The deviation $\Delta F = \pm 2$ kHz is centered around each SAT tone.
3. *Fade timing status of SAT.* The transmitter is turned off if no valid SAT tone can be detected or the measured SAT does not agree with the SAT color code (SCC) of each cell site transmitted by the control signal, or if no SAT is received when the timer counts to 5 s. SCC is indicated in the set-up channel.

Signaling tone. Signaling tones must be kept within 10 kHz ± 1 Hz and produce a nominal frequency deviation of ±8 kHz of the carrier frequency. It is used over the voice channel. It serves three functions.

1. Flush for special orders
2. Terminate the cells
3. Order confirmation

Malfunction timer set at 60 s. The transmission will cease when the timer exceeds 60 s. The timer never expires as long as the proper sequence of operations is taking place.

3.2.6 Call processing

Initialization. When the user turns on the mobile station, the initialization work starts.

1. Mobile station must tune to the strongest dedicated control channel (usually one of 21 channels) within 3 s. Then a system parameter message should be received.
2. If it cannot complete this task on the strongest dedicated control channel, it turns to the second strongest dedicated control channel and attempts to complete this task within the next 3-s interval.
3. Check whether it is in Enable or Disable status. Serving system status changed to Enable if the preferred system is System A. Serving system status changed to Disable if the preferred system is System B.

Paging channel selection

1. The mobile station must then tune to the strongest paging channel within 3 s. Usually paging channels are control channels.
2. Receive an overhead message train and update the following: Roam, system identification, local control status.

Idle stage. A mobile station executes each of four tasks at least every 46.3 ms.

1. *Responds to overhead information.* Compare SID_s (stored) with SID_r (received). If $SID_s \neq SID_r$, return to initialization stage.
2. *Page match.* If the roam status is Disable, the mobile station must attempt to match for one-word message or two-word messages. If the roam status is Enable, the mobile station must attempt to match two words.
3. *Order.* After matching the MIN, respond to the order.

4. *Rescan access channels.* Because the vehicle is moving, information must be updated. Rescan at 2- to 5-min intervals, depending on different manufacturers.

Call initiation. Origination indication (system access task).

1. *System access task.* When the system access task is started, an access timer is set for

Origination	max 12 s
Page response	max 6 s
An order response	max 6 s
Registration	max 6 s

2. *Scan access channels.* Choose one or, at most, two channels with the strongest signals. If the service request cannot be completed on the strongest signal, the mobile station can select the second strongest access channel (called the *alternate access channel*).
3. *Seize reverse control channel* (RECC).
   a. BIS = 1 status: The mobile station is ready for sending. The land station may ask the mobile station to check and wait for overhead message (WFOM) bit.

WFOM = 1	The mobile station waits to update overhead information (see item 5).
WFOM = 0	Delay a random time (0 to 92 ms) and send service request. It is an access attempt.

   b. BIS = 0 status: This is the status of a "busy" condition. The mobile station increments NBUSY by 1, and then has to wait a random time interval of 0 to 200 ms to check the BIS status (0 to 1) again. When NBUSY exceeds MAXBUSY the call is terminated.
4. *Access attempt parameters.* Maximum of 10 attempts. There is a random delay interval of 0 to 92 ± 1 ms for each attempt at checking the status of BIS. If BIS = 1, the mobile station just waits for the transmitting power to come up and sends out the service request message. The random time delay is used to avoid two or more mobile stations requesting services at the same time.
5. *Update overhead information.* Update overhead information should be completely received by the mobile station within 1.5 s after a call is initiated. Update overhead information is as follows.

   Overhead information (OHD). The OHD will be sent by the land station and updated by the mobile station.

a. Overhead control message (whether the system is overloaded or not)
b. Access type parameter message sets the busy-idle status bits in the BIS field.
c. Access attempt parameters message provides the following parameters.
   (1) Maximum number of seizure tries allowed
   (2) Maximum number of busy occurrences

After the update overhead information has been completely received, the mobile station waits a random time interval of 0- to 750-ms and enters the seize reverse control channel task stated in item 3.

6. *Delay after failure.* The mobile station must examine the access timer every 1.5 s; if it does not expire it reenters the access task after failure. The three failure conditions are as follows.
   a. Collision with other mobile station messages. If the collision occurs before the first 56 bits, the BIS changes from 1 to 0.
   b. The land station does not receive the signaling bits. the BIS remains 1 after the mobile station has sent 104 bits.
   c. The land station receives all the signaling bits but cannot interpret them and respond.

   When these conditions occur, the mobile station must wait a random time before making the next attempt. A random delay should be in the interval of 0 to 200 ms.
7. *Service request message.* A whole package of service request messages must be continuously sent to the land station. The format of each signaling word is shown in Fig. 3.4. There is a maximum length to the message consisting of five words: A, B, C, D, E. After a complete message is sent by the mobile station, an unmodulated carrier follows for 25 ms to indicate the end of the message.
8. *Await message response.* If there is no response after the request is sent for 5 s, the call is terminated, and a 120-impulse-per-minute fast tone is generated to the user. If decoded MIN bits match within 5 s, the mobile station must respond with the following messages.
   a. If access is an *origination* or *page response.*
      (1) Initiate voice channel designation message. Update the parameters as set in the message.
      (2) For a directed-retry message the mobile station must examine the signal strength on each of the retry channels and choose up to two channels with the strongest signals. The mobile station must then tune to the strongest retry access channel.

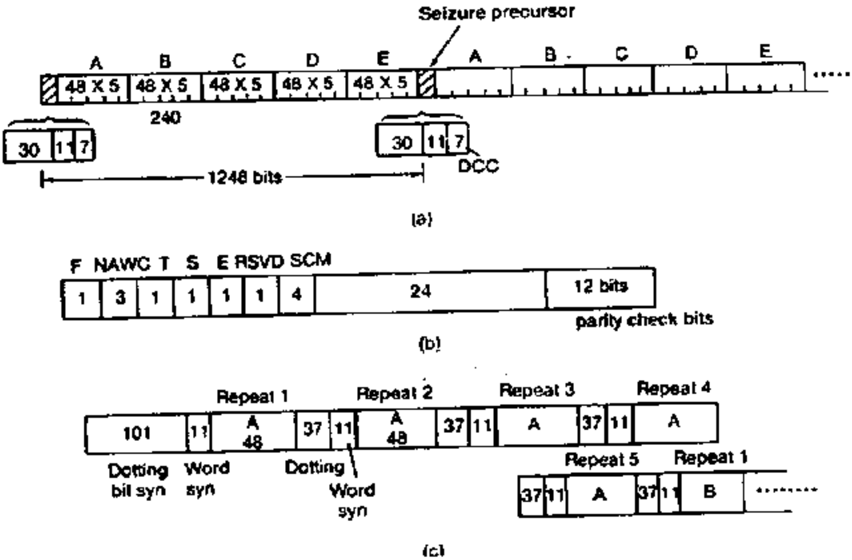


Figure 3.4. Signaling format of both RECC and RVC. (*a*) Reverse control channel (RECC) data stream. (*b*) A message word of RECC. (*c*) Signaling format of RVC.

b. If the mobile station encounters the start of a new message before it receives the directed-retry message, the call has to be terminated.

3.2.7 Mobile station controls on the voice channel

Loss of radio-link continuity. While the mobile station is tuned to a voice channel, a fade timer must be started when no SAT tone is received. If the fade timer counts to 5 s, the mobile station must turn off.

Confirm initial voice channel. Within 100 ms of the receipt of the initial voice channel designation, the mobile station must determine that the channel number is within the set allocated to the home land station or from the other source.

Alerting

I. Waiting for order
   A. If an order cannot be received in 5 s, terminate the call.

B. Order received. If order is received within 100 ms, the action to be taken for each order is
   1. *Handoff*
      a. Turn off the home land station.
         (1) a 10-kHz signal tone is on for 50 ms after the SAT tone.
         (2) Turn off signaling tone.
         (3) Turn off transmitter.
      b. Turn on the new site, adjust power level.
         (1) Turn to new channel.
         (2) Adjust to new SAT.
         (3) Set SCC (signaling color code).
         (4) Turn on new transmitter.
   2. *Alert.* Turn on signaling tone, run 500 ms, and enter the Waiting for Answer task.
   3. *Release*
      a. Send signaling tone for 1.8 s.
      b. Stop sending signaling tone.
      c. Turn off the transmitter.
   4. *Audit.* Send order confirmation message to land station, remain in Waiting for Answer task, and reset the order timer for 5 s.
   5. *Maintenance.* Turn on signaling tone, run for 500 ms, and enter the Waiting for Answer task.
   6. *Change power*
      a. Adjust the transmitter to new ordered level.
      b. Send order confirmation to the land station.
      c. Local control. If the local control option is enabled in the mobile station, the local control order can be enabled if the group identification matches the SID_p in the mobile station's permanent security memory. A system operator can have a "local control" order for several markets and order under a group identification.

II. Waiting for answer. After requesting orders from the land station, the mobile station is in the Waiting for Answer status. An alert time must be set to 65 s. If no answer comes back in 65 s, the call is terminated. Events occur in the same order as listed in the Waiting for Order section above.

Conversation. A release-delay timer must be set to 500 ms during the conversation. The task can be used for the following conditions.

1. If the user terminates the call.
2. If the user requests a flush.

3. Within 100 ms of receipt of any orders, action will be taken by the mobile station for each order

3.2.8 Signaling format

Signaling rate. The signaling rate is 10 kbps ± 1 bps. It is slow enough to not cause the intersymbol interference. The Manchester code waveform is applied so that the energy of this signaling waveform is concentrated at 10 kHz, which can be distinguished from the energy concentrated around the carrier frequency for the baseband voice. (See Fig. 3.3*c*.)

Signaling format. The reverse control channel (RECC) data stream is shown in Fig. 3.4*a*. The first word of 48 bits is called the *seizure precursor*, which consists of 30 synchronization bits, 11 frame bits, and 7 coded DCC (digital color code) bits.

Function	Coding
30 synchronization bits	10101010--
11 frame bits (word synchronization)	11100010010
7-bit coded DCC (00)	0000000
(01)	0011111
(10)	1100011
(11)	1111100

Each information word contains 48 bits. Each word block contains 240 bits, where each word is repeated five times.

The maximum data stream is one seizure precursor plus five word blocks: A, B, C, D, and E. The total number of bits is 1248 bits as shown in Fig. 3.4*a*.

In each information word, 36 bits are information bits and the other 12 bits are parity check bits, formed by encoding 36 bits into a (48, 36) BCH code that has a Hamming distance of 5 (described in Chap. 13). The format is shown in Fig. 3.4*b* for the first word. The interpretation of the data field is as follows.

F	First word indication field, 1—first word, 0—subsequent words
NAWC	Number of additional words coming
T	T field, 1—indicates an origination, 0—indicates page response
S	S field, 1—send serial number word, 0—otherwise
E	Extended address field, 1—extended address word sent, 0—not sent
SCM	Station class mark field (see Sec. 2.2.1)

Types of messages. The types of messages to be transmitted over the reverse control channel (RECC) are:

- Page response message. When the mobile station receives a page from the land station, the mobile station responds back.
- Origination message. The mobile station originates the call.
- Order confirmation message. The mobile station responds to the order from the land station.
- Order message. The mobile station orders the tasks which should be performed by the land station and the mobile transmission switching office (MTSO).

Function of each word

Word A	An abbreviated address word. It is always sent to identify the mobile station.
Word B	An extended address word. It will be sent on request from the land station or in a roam situation. In addition, the local control field and the other field are shown in this word.
Word C	A serial number word. Every mobile unit has a unique serial number provided by the manufacturer. It is used to validate the eligible users.
Word D	The first word of the called address.
Word E	The second word of the called address.

Reverse voice channel (RVC). The reverse voice channel (RVC) is also used by a wideband data stream sent from the mobile station to the land station. A 10 kbps $\pm$ 1 bps data stream is generated. A word is formed by encoding the 36 content bits into a (48, 36) BCH code, the same as the RECC.

1. *Signaling format.* The first 101 syn bits are used for increasing the possibility of successful syn. The signaling format of RVC is shown in Fig. 3.4*c*. There are two words: The first word repeats five times, and then the second word repeats five times.
2. *Types of messages.* There are two types of messages:
   a. Order confirmation message (one word) responds to the land station to confirm the order, e.g., handoff confirmation.
   b. Called-address message (two words) establishes a three-party call.

3.3 Specification of Land Station (United States)[1-3]

Most parts in the specification of the land station are the same as the specification of the mobile station, such as the modulation of voice signals (sec. 3.2.2), security and identification (Sec. 3.2.4),and supervision (Sec. 3.2.5). These sections will not be repeated in the specification of the land station.

3.3.1 Power

Maximum effective radiated power (ERP) and antenna height above the average terrain (HAAT) must be coordinated locally on an ongoing basis. Maximum power is 100 W at a HAAT of 500 ft. Normally, the transmitting 20 W at an antenna height of 100 ft above the local terrain is implemented.

3.3.2 Limit on emission

The field strength limit at a distance of 100 ft or more from the receiver is 500 μV/m.

3.3.3 Call processing

Call processing is the land station operation that controls the mobile station.

Overhead functions for mobile station initiation. The overhead message train contains the first part of the system identification (SID1) and the number of paging channels (N).

On control channel

1. Overhead information is sent on the forward control channel and requires all mobile stations to either update or respond with new information during a system access.

   Update the following information
   - First part of the system identification (SID1)
   - Serial number (S). If S = 1, all mobile stations send their serial numbers during a system access; if S = 0, no need to send serial number.
   - Registration (REGH, REGR). The land station is capable of registering the mobile stations.

REGH = 1 Enables registration for home mobile stations
REGH = 0 Qtherwise
REGR = 1 Enables registration for roaming mobile stations
REGR = 0 Otherwise

- Extended address (E)

E = 1 Both MIN1 and MIN2 required
E = 0 Otherwise

- Discontinuous transmission (DTX)

DTX = 1 Let mobile stations use discontinuous transmission mode on the voice channel (reducing power consumption for portable units)
DTX = 0 Otherwise

- Number of paging channels (N)
- Read control-filler message (RCF) (see Sec. 3.3.4)

RCF = 1 ask the mobile unit to read control-filler message before accessing a system on a reverse control channel
RCF = 0 Otherwise

- Combined paging/access (CPA)

CPA = 1 Paging channel and access channel are the same
CPA = 0 Paging channel and access channel are not the same

- Number of access channel (CMAX)

Respond with the following information

- Local control. A system operation for home mobile stations and for the roaming mobile stations that are members.
- New access channels (NEWWACC). Send NEWACC information along the first access channel.
- Registration increment (REGINCR). Each time the mobile station increments a fixed value received on FOCC for its updated registration ID if it is equipped for autonomous registration.
- Registration ID (REGID). The last registration number received on FOCC and stored at the mobile station. Every time an increment occurs REGID (new) = REGID (old) + REGINCR, the mobile station identifies itself to a land station.
- Rescan. The rescan global action message must be sent to require all mobile stations to enter the initialization task.

2. The land station will use a control message (one word or two words) to page a mobile station through its home land station. The roaming mobile station must be paged with a two-word message.
3. Orders must be sent to mobile stations with a two-word control message. The orders can be audit and local control. By sending local orders with the order field set to local control and using system identifications (SID) that have identical group identifications, a home mobile station or a roaming mobile station which is a member of a group can be distinguished.

Land station support of system access

1. *Overhead information.* The following information must be sent on a forward control channel to support system access which is used by mobile stations.
   - *Digital color code* (DCC). The mobile station uses DCC to identify the land station.
   - *Control mobile attenuation code* (CMAC). When a control-filler message is transmitted, the mobile station receiving the code has to adjust its transmitter power level before accessing a system on a reverse control channel.
   - *Wait for overhead message* (WFOM). Set WFOM to 1 in the control-filler message; then the mobile station must wait for WFOM before accessing a system on a reverse control channel.
   - *Overload control* (OLC). The mobile stations that are assigned to one or more of the 16 overload classes (N = 1 to 16) must not access the system for originations on the RECC.
   - *Access-type parameters.* When the access-type parameters' global action message with the BIS field set to 0 is appended to a system parameter overhead message, the mobile stations do not check for an idle-to-busy status.
   - *Access-attempt parameters* are the limit on the number of "busy" occurrences for mobile stations or the default values for the number of seizure attempts.
2. *Reverse control channel seizure by a mobile station.* When this equals 1 all mobile stations must check for an idle-to-busy status when accessing a system. A seizure precursor (48 bits including coded DCC) sent by a mobile station and received by the land station should match its encoded form of DCC.

   It must set the status of the busy-idle bits on the forward control channel between 0.8 and 2.9 ms of receipt of the last bit of 48 bits of the seizure precursor. The busy-idle bits must remain busy until
   - 30 ms after the last word of message has been received

- (24 N + 55) ms otherwise, where N is the maximum number of words. It will not exceed 175 ms.

3. *Response to mobile station messages.* It is not required that the land station respond to the mobile station message. During periods of system overload or high usage, it may be desirable to permit mobile stations to "time-out" rather than sending release or other orders which use system capacity. The usual time-out period is 5 s. It means that after 5 s, if the mobile station does not receive any response from the land station, the mobile station terminates the transmitted power. The following responses to mobile stations may be sent:
   a. Origination message. Send one of the following orders.
      (1) Initial voice channel designation
      (2) Directed retry—direct to other cell site
      (3) Intercept—priority feature
      (4) Reorder—initiate again
   b. Page response message. Send one of the following orders.
      (1) Initial voice channel designation
      (2) Directed retry
      (3) Release—turn off signaling tone and release the channel
   c. Order message. Send one of the following orders.
      (1) Order confirmation
      (2) Release
   d. Order confirmation message. "No message is sent."

Mobile station control on voice channel. The change of status of the supervisory audio tone (SAT) and signaling tone (ST) are used to signal the occurrence of certain events during the progress of a call, such as confirming orders, sending a release request, sending a flash request, and loss of radio-link continuity. In addition to the analog signaling (SAT and ST) to and from the mobile station, digital messages (in a burst mode with 10 kbps transmission rate) can be sent to and received from the mobile station. Response to the digital message is either a digital message or a status change of SAT and ST.

We use the notation "(SAT, ST) status" to describe the signaling condition.

SAT		ST		(SAT, ST) status	Conditions
On	Off	On	Off		
1			0	(1,0)	Mobile off-hook
1		1		(1,1)	Mobile on-hook
	0	1		(0,1)	Mobile in fade
	0		0	(0,0)	Mobile transmitter off

1. *Loss of radio-link continuity.* A designated SAT tone is continuously sent to the mobile station; the same SAT should be sent back on a reverse voice channel. If within 5 s the SAT has not been received, the land station would assume that the mobile station is lost and terminates the call.
2. *Initial voice channel confirmation*
   a. Confirmation will be received by the land station as a change in the SAT, ST status from (0,0) to (1,0).
   b. If the confirmation is not received, the land station must either resend the message or turn off the voice channel transmitter.
   c. If the mobile station was paged, the land station must enter the Wait for Order task or Conversation task.
3. *Alerting*
   a. *Waiting for Order task.* After being paged, the mobile station confirms the initial voice channel designation.
      (1) *Handoff.* The mobile station confirms the order by a change in the (SAT, ST) status from (1,0) to (1,1) for 50 ms. The land station must remain in the Waiting for Order task.
      (2) *Alert.* The mobile station confirms the order by changing (SAT, ST) status from (1,0) to (1,1). The land station must then enter the Waiting for Answer task.
      (3) *Release.* The mobile station confirms the order by a change of (SAT, ST) status from (1,0) to (1,1) and holds the (1,1) status for 1.8 s. The land station must then turn off the transmitter.
      (4) *Audit.* The mobile station confirms the order by a digital message. The land station remains in the Waiting for Order task.
      (5) *Maintenance.* The mobile station confirms the order by a change in (SAT, ST) status from (1,0) to (1,1). The land station remains in the Waiting for Order mode.
      (6) *Change power.* The mobile station confirms the order by a digital message.
      (7) *Local control.* The confirmation and action depends on the message.
   b. *Waiting for Answer task.* When this task is entered, an alert timer must be set for 30 s. The following orders can be sent:
      (1) *Handoff.* The mobile station confirms the order by a change of (SAT, ST) status from (1,1) to (1,0) for 500 ms followed by (1,0) to (1,1) held for 50 ms on the old channel. Then (1,1) status is sent on the new channel.
      (2) *Alert.* If no confirmation is received, the land station must reset the alert timer to 30 s.

(3) *Stop alert.* The mobile station confirms the order by a change of (SAT, ST) status from (1,1) to (1,0).

(4) *Release.* The mobile station confirms the order by changing (SAT, ST) status from (1,1) to (1,0) for 500 ms followed by a change of (SAT, ST) from (1,0) to (1,1), which is then held for 1.8 s. The land station must turn off the transmitter.

(5) *Audit.* The mobile station confirms the order by a digital message.

(6) *Maintenance.* If no confirmation is received, the land station resets the alert timer to 30 s.

(7) *Change power.* The mobile station confirms the order by a digital message (see Sec. 3.2.1).

(8) *Local control.* The confirmation and action depends on the message.

4. *Conversation.* The mobile station signals an answer by a change in the (SAT, ST) status from (1,1) to (1,0). The land station enters the conversation task.

   a. Handoff. The mobile station confirms the order by a change in the (SAT, ST) from (1,0) to (1,1), which is then held for 50 ms. Then the land station must remain in the Conversation task.

   b. Send called address. The called mobile station confirms the order by a digital message with the called address information. This feature would save the established link if the called address were in error because of the transmission medium.

   c. The functions *alert, release, audit, maintenance,* and *local control.* Same as in the Waiting for Order task.

   d. Change power. The mobile station confirms the order by a digital message.

   e. Flash request. The mobile station signals a flash by changing (SAT, ST) from (1,0) to (1,1) then holding (1,1) for 400 ms, then following with a transition to (1,0).

   f. Release request. The mobile station signals a release by changing the (SAT, ST) status from (1,0) to (1,1), which is then held for 1.8 s. The land station must turn off the transmitter. This would be used for the mobile user who dials a called number and decides to terminate for any reason.

3.3.4 Signaling formats

Forward control channel (FOCC). The FOCC is a continuous wideband 10 kbps $\pm$ 0.1 bps data stream sent from the land station to the mobile station. Each forward control channel consists of three discrete information streams (see Fig. 3.5):

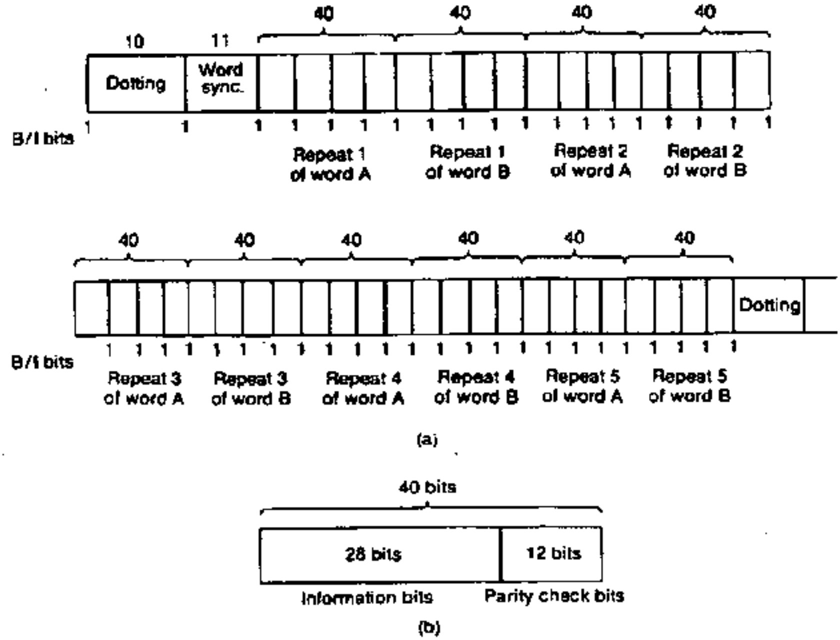


Figure 3.5 Forward control channel message stream (land-to-mobile). (*a*) Signaling format of FOCC. (*b*) A message word of FOCC.

Stream A (least significant bit of MIN = 0)

Stream B (least significant bit of MIN = 1)

Busy-idle stream (busy = 0, idle = 1); it is at a 1 kbps rate, i.e., one busy-idle bit every 10 data bits.

The 10-bit dotting sequence (1010101010) is for bit syn. The 10-bit length is assumed to be sufficient for bit syn because the mobile station is always monitoring the FOCC after initialization (see 3 2.6). The frame syn bits are the Barker sequence (11100010010). A word is formed by coding 28 control bits into a (40, 28, 5) BCH code. The total number of bits is 40, the number of information bits is 28, and the hamming distance is 5. The hamming distance d can be translated to the capability of error correction bits, t, as follows:

$$t = \frac{d - 1}{2} = 2$$

Since this code will detect errors as well as correct them, it reduces to correct one bit in error and assure detection of two bits in error.

2	2	24	12
T_1T_2	DCC	$MIN1_{23\text{-}0}$	P

(a)

2	2	10	1	5	3	5	12
T_1T_2 = 10	SCC = 11	$MIN2_{33\text{-}34}$	RSVD = 0	Local	OrdQ	Order	P

(b)

2	2	10	3	11	12
T_1T_2 = 10	SCC ≠ 11	$MIN2_{33\text{-}24}$	VMAC	Chan	P

(c)

DCC (from FOCC)	7 bit coded DCC on RECC	SCC	
0 0	0 0 0 0 0 0 0	SCC ≠ 11: 0 0	5970 Hz
0 1	0 0 1 1 1 1 1	SCC ≠ 11: 0 1	6000 Hz
1 0	1 1 0 0 0 1 1	SCC ≠ 11: 1 0	6030 Hz
1 1	1 1 1 1 1 0 0	1 1	Not a channel designation

(d)

Figure 3.6 Mobile station control message. (*a*) Word 1—abbreviated address word (the busy-idle stream is not shown); (*b*) word 2—extended address word (SCC = 11); (*c*) word 2—extended address word (SCC ≠ 11); (*d*) DCC and SCC codes.

The code is a shortened version of the primitive (63,51,5) BCH code. It has 12 parity check bits. As long as the 12 parity check bits are retained, the shortened version can be any length. We use (40,28,5), for which a message of 28 bits is suitable (see Fig. 3.5*b*). The transmission rate is 10 kbps. The throughput is 1200 bps (see Fig. 3.5*a*).

Types of messages

1. *Mobile station control message.* Consists of one, two, or four words.
   a. *Word 1.* Abbreviated address word (see Fig. 3.6*a*), T_1T_2 = type field.
      $T_1T_2 = 00$ Only word 1 is sent
      $T_1T_2 = 01$ Multiple words are sent.
      DCC—digital color code field, 2 bits sent on FOCC. Then it is received by the mobile station and translated to a 7-bit coded DCC on RECC (see Fig. 3.6*d*).

Overhead message types

Code	Order
000	registration ID
001	control-filler
010	reserved
011	reserved
100	global action
101	reserved
110	word 1 of system parameter message
111	word 2 of system parameter message

(a)

2	2	20	1	3	12
T_1, T_2	DCC	REGID	END	OHD	P

(b)

Figure 3.7 Overhead message types and format.

b. Words 2 to 4. Extended address word $T_1T_2 = 10$, set in each additional word (see Fig. 3.6*b* and *c*). Let SCC = 11 or SCC ≠ 11 (see two bits indicated in Fig. 3.6*d*).

(1) *Word 2*

(*a*) By combining "order code" (ORDER) and "order qualification code" (ORDQ) in this word (see Fig. 3.6*b*), we can describe 11 functions.

Page (or origination)	Registration
Alert	Intercept
Release	Maintenance
Reorder	Send called address
Stop alert	Direct-retry status
Audit	

(*b*) Also changes the mobile station power levels in eight levels

(2) *Word 3.* First directed-retry word

(3) *Word 4.* Second directed-retry word.

2. *Overhead message (OHD).* A 3-bit OHD field (see Fig. 3.7*a*) is used to identify the overhead message types. It locates just before the 12 parity check bits shown in Fig. 3.7*b*. The overhead types are grouped into the following functional classes.

a. System parameter overhead message. The system parameter overhead message must be sent every 0.8 ± 0.3 s. It consists of two words: word 1 contains the first part of the system identi-

	BS	WS	Word	BS	WS	Word	BS	WS	Word	. . . . .
FVC	101	11	40	37	11	40	37	11	40	(28, 12)
RVC	100	11	48	37	11	48	37	11	48	(36, 12)

Repeat 11 times for FVC
Repeat 5 times for RVC

BS - Bit sync.
WS - Word sync.

Figure 3.8 Signaling format of FVC and RVC.

fication field, and word 2 contains the number of paging channels and number of access channels.

b. Global action overhead message. There are many global action overhead messages. Each of them consists of one word. The actions are registration increment, new access channel starting point, maximum busy occurrences, maximum seizure tries, etc.

c. Registration ID message. It consists of one word containing the registration ID field.

d. Control-filler message. It consists of one word and is sent whenever there is no other message to be sent on FOCC. It is used to specify a control mobile attenuation code (CMAC) which is used by mobile stations accessing the system, and a Wait for Overhead Message bit (WFOM) indicating whether mobile stations must read an overhead message train before accessing the system.

3. Data restriction

   a. The overhead message transmission rate is about once per second.

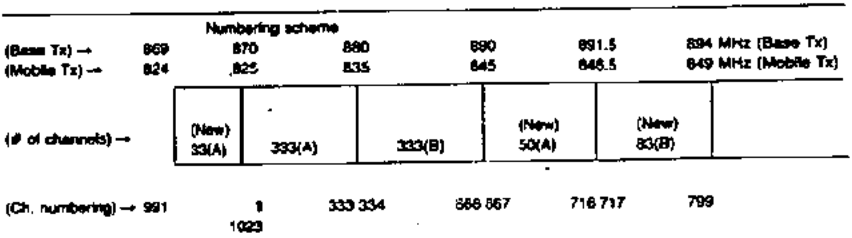
   b. Design the control-filler message to exclude the frame-sync (word sync) sequence.

   c. Restrict the use of certain control office codes.

Forward voice channel (FVC). During the call period, FVC is used for signaling. At the beginning, the 101-bit dotting sequence is used for bit sync then for all the repeat dotting sequences; each of them only contains 37 bits, as shown in Fig. 3.8. The word length is 40 bits and repeats 11 times. The reason for repeating 11 times is to be sure that the handoff message would reach the mobile station before the signal dropped below the unacceptable level at the mobile station. The FVC signaling is mainly used for handoff, and the signal level when the handoff occurs is usually very weak. Therefore, the purpose of the FVC is to be sure that the mobile station will get the message and not have a chance to send back a response on receipt because of a weak signal condition.

3.3.5 Additional spectrum radio (ASR) issues

The FCC has allocated an additional 83 voice channels to each system (Band A and Band B). ASR will have 832 channels, half of them, 416 channels (333 channels plus 83 channels), are operated for each system. The 21 control channels still remain the same, but the total number of voice channels becomes 395. The new numbering scheme is shown below.



ASR is identified by using the station class mark field as shown in Fig. 3.4*b*. The station class mark (SCM) consists of 4 bits and is specified as shown below.

Power class	SCM	Transmission	SCM	Bandwidth	SCM
Class I (4 W)	XX00	Continuous	X0XX	20 Mhz	0XXX
Class II (1.2 W)	XX01	Discontinuous	X1XX	25 MHz (ASR)	1XXX
Class III (0.6 W)	XX10				
Reserved	XX11				

The new frequency management charts for Block A and Block B are shown in Table 3.1.

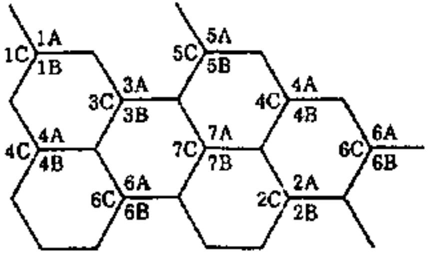
3.4 Different Specifications of the World's Analog Cellular Systems

In general, cellular systems can be classified by their operating frequencies: 450-MHz or 800-MHz. Also, they can be distinguished by the spacing between their channels (also called the *channel bandwidth*): 30, 25, or 20 kHz. Japanese NTT has deployed a 12.5-kHz channel spacing in their cellular system.

The large-capacity cellular telephones used in the world are listed in Table 3.2. There are five major systems, and their message protection schemes are different. The major differences are

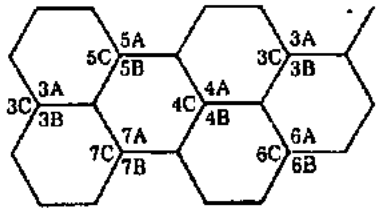
TABLE 3.1 New Frequency Management (Full Spectrum) Block A

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												102	103	104	105
106	107	108	109	110	111												123	124	125	126
127	128	129	130	131	132												144	145	146	147
148	149	150	151	152	153												165	166	167	168
169	170	171	172	173	174												186	187	199	190
190	191	192	193	194	195												207	208	209	210
211	212	213	214	215	216												228	229	230	231
232	233	234	235	236	237												249	250	251	252
253	254	255	256	257	258												270	271	272	273
274	275	276	277	278	279												291	292	293	294
295	296	297	298	299	300												312	X	X	X
313*	314	315	316	317	318	319	320	321	322	323	324	325	326	327	328	329	330	331	332	333
667	668	669	670	671	672	673	674	675	676	677	678	679	680	681	682	683	684	685	686	687
688	689	690	691	692	693	694	695	696	697	698	699	700	701	702	703	704	705	706	707	708
709	710	711	712	713	714	715	716	X	991	992	993	994	995	996	997	998	999	1000	1001	1002
1003	1004	1005	1006	1007	1008	1009	1010	1011	1012	1013	1014	1015	1016	1017	1018	1019	1020	1021	1022	1023



Block B

1A	2A	3A	4A	5A	6A	7A	1B	2B	3B	4B	5B	6B	7B	1C	2C	3C	4C	5C	6C	7C
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														375
376	377	378	379	380	381	382														396
397	398	399	400	401	402	403														417
418	419	420	421	422	423	424														438
439	440	441	442	443	444	445														459
460	461	462	463	464	465	466														480
481	482	483	484	485	486	487														501
502	503	504	505	506	507	508														522
523	524	525	526	527	528	529														543
544	545	546	547	548	549	550														564
565	566	567	568	569	570	571														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
626	628	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	717	718	719
720	721	722	723	724	725	726	727	728	729	730	731	732	733	734	735	736	737	738	739	740
741	742	743	744	745	746	747	748	749	750	751	752	753	754	755	756	757	758	759	760	761
762	763	764	765	766	767	768	769	770	771	772	773	774	775	776	777	778	779	780	781	782
783	784	785	786	787	788	789	790	791	792	793	794	795	796	797	798	799				



*Boldface numbers indicate 21 control channels for Block A and Block B respectively.

TABLE 3.2 Large-Capacity Analog Cellular Telephones Used in the World

	Japan	North America	England	Scandinavia	Germany
System	NTT	AMPS	TACS	NMT	C450
Transmission frequency (MHz):					
Base station	870–885	869–894	917–950	463–467.5	461.3–465.74
Mobile station	925–940	824–849	872–905	453–457.5	451.3–455.74
Spacing between transmission and receiving frequencies (MHz)	55	45	45	10	10
Spacing between channels (kHz)	25, 12.5	30	25	25	20
Number of channels	600	832 (control channel 21 × 2)	1320 (control channel 21 × 2)	180	222

Coverage radius (km)	5 (urban area) 10 (suburbs)	2–20	2–20	1.8–40	5–30
Audio signal:					
Type of modulation	FM	FM	FM	FM	FM
Frequency deviation (kHz)	±5	±12	±9.5	±5	±4
Control signal:					
Type of modulation	FSK	FSK	FSK	FSK	FSK
Frequency deviation (kHz)	±4.5	±8	±6.4	±3.5	±2.5
Data transmission rate (kb/s)	0.3	10	8	1.2	5.28
Message protection	Transmitted signal is checked when it is sent back to the sender by the receiver.	Principle of majority decision is employed.	Principle of majority decision is employed.	Receiving steps are predetermined according to the content of the message.	Message is sent again when an error is detected.

SOURCE: Report from International Radio Consultative Committee (CCIR).

TABLE 3.3 World's Analog Cellular Systems

NTT	AMPS	TACS	NMT	C450	NEC
Japan	U.S.	England	4 Nordic countries	Germany	Australia
	Canada	Hong Kong	Spain		Singapore
	South Korea	China	The Netherlands		Hong Kong
	Hong Kong		Belgium		Jordan
	Taiwan		Oman		Colombia
	Australia		Saudi Arabia		Mexico
	China		Tunisia		Kuwait
	Mexico		Malaysia		
	Brazil		Australia		
	Argentina		Ireland		
	Chile				

SOURCE: Report from International Radio Consultative Committee (CCIR).

1. The principle of majority decision (PMD)
2. The automatic repeat request (ARQ)

These schemes each have their merits. In a very severe fading environment, PMD is a good candidate. In a fairly light fading environment, ARQ is a good candidate. Table 3.3 lists the system of each country's use. There are 25 countries which have cellular systems.

Today there is no compatibility among the analog cellular systems serving European countries. In 1982, they agreed to set up a pan-European digital cellular standard, called GSM (special mobile group) specification, which was implemented in 1992 and is described in Chap. 15.

References

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