Chapter

16

Intelligent Cell Concept and Applications

16.1 Intelligent Cell Concept

16.1.1 What is the intelligent cell?

In the cellular industry, system capacity is a great issue. As demand for cellular service grows, system operators try to find ways to increase system capacity. Capacity can be increased by reducing the cell sizes. This is called the *conventional microcell approach,* but it does not provide intelligence. When the cell size becomes smaller, the control of interference among the cells becomes harder. Also, the handoff time from the beginning of the initiation to the action completion sometimes may take around 15 s. If a mobile station is moving at a speed of 25 km/h (7 m/s), then the mobile station will travel 105 m in 15 s; at a speed of 50 km/h, the mobile station travels 205 m in 15 s. Since within a microcell of 0.5-km radius the overlapped region for a handoff is very small, then the mobile station is in the overlapped region too short a time for the handoff action to be complete. As a result, the call drops. In a conventional microcell system, interference is hard to control and the handoffs may not have enough time to complete.

The intelligent cell can solve the two problems. The intelligent cell concept can be used not only in microcells but also in regular cells to bring extra capacity to the system.

There are two definitions to describe an intelligent cell. One definition of intelligent cell is that the cell is able to intelligently monitor where the mobile unit or portable unit is and find a way to deliver confined power to that mobile unit. The other definition of intelligent cell is that signals coexist comfortably and indestructibly with the interference in the cell. From the first definition, the intelligent cell is called the *power-delivery intelligent cell,* and from the second definition, it is called the *processing-gain intelligent cell.* The intelligent cell may be a large cell such as a macrocell or a small cell such as a microcell. The intelligent cell increases capacity and improves performance of voice and data transmission. Since personal communication service (PCS) needs vast capacity and high quality, the intelligent cell concept is well-suited to it. Actually, using any means intelligently in a cell to improve the performance of services is what the intelligent cell stands for.

16.1.2 The philosophy of implementing power-delivery intelligent cells

Many different wireless versions of an intelligent cell can be used as long as they can deliver power to the location of the mobile unit. The easiest explanation is the analogy of a person entering a house (Fig. 16.1). In a conventional macrocell or microcell, when a mobile unit enters a cell or a sector, the cell site will cover the power to the entire cell or sector. This is because the cell site does not know where the mobile unit is within the cell or sector. This is just like a house that turns on all the lights when a person enters it.

Delivering power intelligently. In an intelligent macrocell or microcell, when a mobile unit enters a cell or a sector, the cell site covers only a local area, which follows the mobile unit. This is just like a house

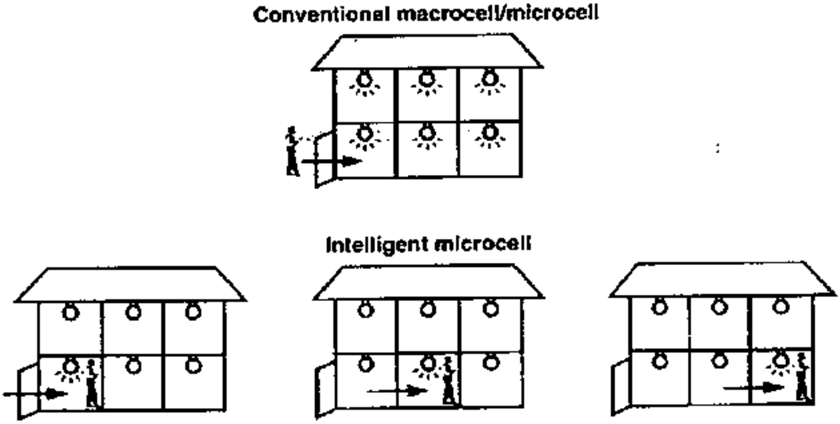


Figure 16.1 Microcell philosophy: energy follows the mobile analogy, light follows the person.

that turns on only the light of the first room a person enters. When the person enters the second room, the light of the first room is turned off and the light of the second room is turned on. Therefore, the light of only one room is on at a time and not the lights in the whole house. When the lights of the entire house A and the lights of the entire house B are on, the two houses should be largely separated in order to avoid the light being seen from one house to the other. If the light of only one room of house A and house B is on, the light that can be seen from one house to the other house is relatively weak. Thus, the distance between the two houses can be much closer.

This same analogy can be applied to a cellular system. In a cellular system, the frequency reuse scheme is implemented for the purpose of increasing spectrum efficiency. If two cochannel cells (cells that use the same frequency) can be placed much closer, then the same frequency channel can be used more frequently in a given geographical area. Thus the finite number of frequency channels can provide many more traffic channels, and both system capacity and spectrum efficiency can be further increased. In order to reduce the separation between two cochannel cells, the power of each cell should be reduced to cover merely one of numerous local areas in a cell if the cell operator is intelligent enough to know in which local area the mobile unit or handset is. Therefore, there are two required conditions:

1. The cell operator has to know where the mobile unit is located. Different resolution methods can be used to locate the mobile unit.
2. The cell operator has to be able to deliver power to that mobile unit. If the power transmitted from the cell site to the mobile unit can be confined in a small area (analogous to the light of a small room turning on when a person enters it), cochannel interference reduces, and the system capacity increases.

The extreme case of interference reduction is to connect the base transmitter and the mobile receiver by a wire. In this case, the wireless communication system becomes a wire line system, and interference is reduced to a minimum.

Radio capacity. In a frequency-reuse system, such as a cellular system, we always use the term *radio capacity* to measure the traffic capacity. The radio capacity m is defined as[1]

$$m = \frac{M}{K} \qquad \text{number of channels/cell} \qquad \text{(for omni cells)} \qquad (16.1\text{-}1)$$

or

$$m = \frac{M}{K \times S} \quad \text{number of channels/sector} \qquad \text{(for sector cells)} \tag{16.1-2}$$

where M is the total number of frequency channels, K is the cell reuse factor, and S is the number of sectors. K can be expressed as[2]

$$K = \frac{1}{3}\left(\frac{D}{R}\right)^2 \tag{16.1-3}$$

D is the cochannel cell separation and R is the cell radius. Also, according to Figure 16.2*a*, the relationship between the carrier-to-interference ratio C/I and D/R can be expressed[3] as

$$C/I = \frac{(D/R)^4}{6} \tag{16.1-4}$$

Equation (16.1-4) is based on the propagation path loss of 40 dB/dec and omni cells. The radio capacity of omni-cell systems is[3]

$$m = \frac{M}{\sqrt{\frac{2}{3}\left(\frac{C}{I}\right)}} \quad \text{channels/cell} \tag{16.1-5}$$

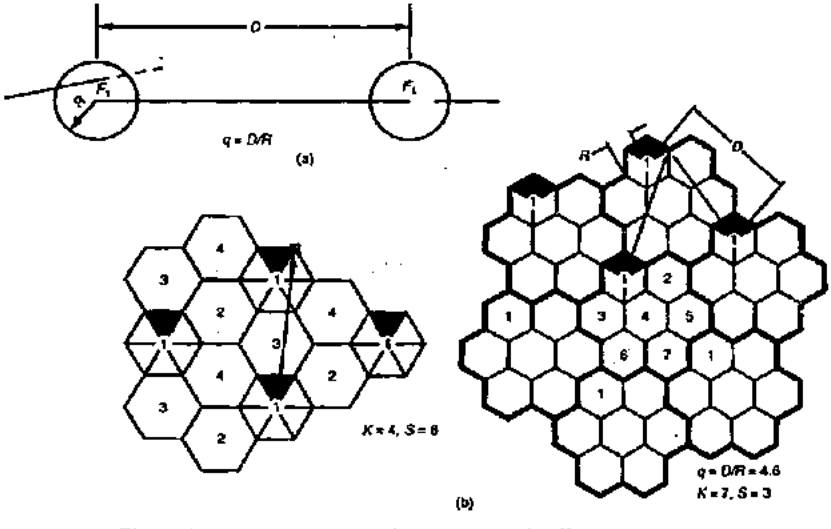


Figure 16.2 The D/R relationship in different sectorial cells.

Any other parameters can be derived from the measures of radio capacity such as erlangs/cell, erlangs/Km^2, and calls/km^2.

The normalized radio capacity is

$$\hat{m} = m/B_T \qquad \text{channel/cell/spectral band} \qquad (16.1\text{-}6)$$

where B_T is the total spectral band. When two systems operate at two different spectral bands such as B_{T_1} and B_{T_2}, then the radio capacities m_1 and m_2 have to be normalized by first using Eq. (16.1-6) to find m_1/B_{T_1} and m_2/B_{T_2} before comparing their radio capacities $\hat{m}_1$ and $\hat{m}_2$.

In a frequency-division multiple-access (FDMA) system, M is the total number of frequency channels, and in a time-division multiple-access (TDMA) system, M is the total number of slot channels. M is a countable number and is fixed, but K is a variable number and depends on cochannel separation D as shown in Fig. 16.2*b*. However, because of the reuse of frequency channels, more traffic channels are generated. If one frequency channel is used 50 times, then the traffic channel becomes 50 M. Based on a $K = 7$ system, the number of cells will be $50 \times 7 = 350$ cells. The radio capacity $m = M/7$ is measured by the number of frequency channels per cell, which is determined by the cell reuse factor K only, and not by the number of total cells in the system. The radio capacity m increases if K is reduced, provided that the voice quality and data performance are maintained according to the specification.

Implementation of the intelligent cell concept may involve using multiple zones, multiple antenna beams, multiple isolated spaces, or any means of eliminating interference. There are many kinds of intelligent cells as described in the following sections, where we will compare their radio capacities.

16.1.3 Power-delivery intelligent cells

Zone-divided cells. In general there are three kinds of zone-divided cell systems.

Sectorial cells. Sectorial cells are used to reduce interference. Usually sectorial cells are used when the terrain contour in the cells is not flat, causing unevenly distributed interference from other cells. There are two kinds of sectorial cells.

- 7-cell/3-sector reuse system ($K = 7$, $S = 3$)
- 4-cell/6-sector reuse system ($K = 4$, $S = 6$)

In both systems, each sector has a set of unique designated channels. The mobile unit moving from one sector or one cell to another sector or cell requires an intracell handoff. Based on a cluster of either $K = 7$ cells or $K = 4$ cells (see Fig. 16.2*b*), the radio capacities of these two systems are

$$m_1 = \frac{M}{7 \times 3} = \frac{M}{21}$$

channels/sector (for a cellular system of $K = 7$ and $S = 3$)

$$m_2 = \frac{M}{4 \times 6} = \frac{M}{24}$$

channels/sector (for a cellular system of $K = 4$ and $S = 6$)

Sectorial cells with intracell handoffs do not increase radio capacity, but cochannel interference (Fig. 16.2) can be reduced as shown below:

$$\frac{C}{I} = \frac{R^{-4}}{(D + 0.7R)^{-4} + D^{-4}} = 285 \text{ or } 24.5 \text{ dB} \qquad (\text{for } K = 7, S = 3) \qquad (16.1\text{-}7)$$

$$\frac{C}{I} = \frac{R^{-4}}{(D + R)^{-4}} = 395 \text{ or } 26 \text{ dB} \qquad (\text{for } K = 4, S = 6) \qquad (16.1\text{-}8)$$

The above calculation is based on the mobile radio propagation path-loss rule of 40 dB/dec. Because only one or two cochannel interfering sectors are affected, as seen in Fig. 16.2, the C/I will improve by about 7 to 8 dB as compared with $C/I = 18$ dB for a $K = 7$ omni-cell system. When large-size cells are implemented because of the variation of the terrain contour, the sectorial cells should be used to gain this additional margin in decibels to overcome long-term fading. However, more frequent handoffs and larger overlapped regions occur in a $K = 4$ cell than in a $K = 7$ cell.

Intelligent microcells.[4] When dividing a cell into many zones as in Fig. 16.3, the cell operator knows which zone the mobile unit is in and delivers the radio signal to that zone. When the mobile unit has been assigned a frequency channel for a call, the frequency channel is always associated with that call within the cell. The cell operator simply turns on the new zone site while the mobile unit is entering and turns off the old zone site when it leaves with the assigned frequency channel to the mobile unit unchanged. With this arrangement, we can find the received C/I value at a mobile unit for a scenario having six co-

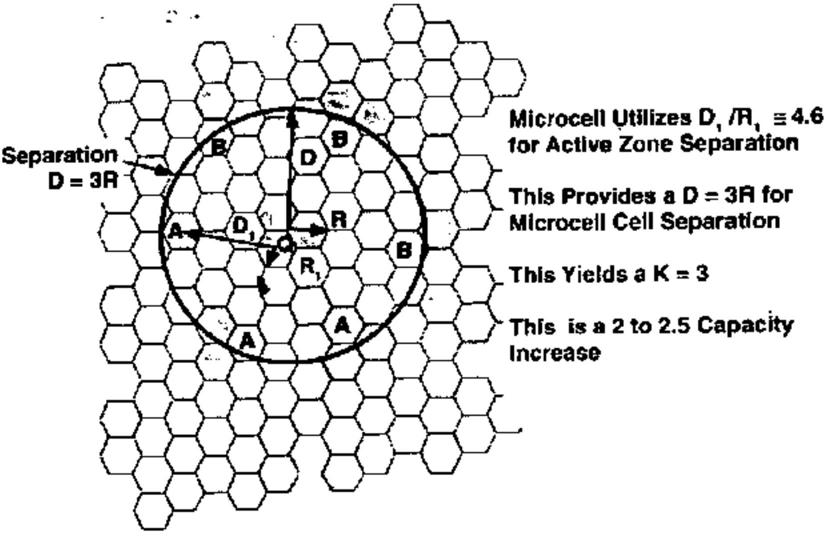


Figure 16.3 Intelligent microcell capacity application.

channel interferers at the first tier surrounding the center cell (Fig. 16.4). It is easy to show that the six interferers at the second tier do not contribute any significant interference to the center cell.[4] Assume, as shown in Fig. 16.3, that the desired mobile unit is in zone Q of the center cell and there are three interfering zones marked A and three interfering zones marked B, one in each interfering cell where the six interfering mobile units could be. This is a worst-case scenario. In this case, the voice quality should be maintained at the stated requirement of $C/I \geq 18$ dB in each zone; that is, the ratio of cochannel zone separation D_1 to zone radius R_1 should be $D_1/R_1 = 4.6$. Based on the six worst interfering zones one in each cell, with their minimum D_1/R_1 being 4.6, we can find the resultant C/I received by the desired mobile unit:

$$C/I = \frac{(R_1)^{-4}}{\underbrace{3(4.6R_1)^{-4}}_{\text{zone A}} + \underbrace{3(5.5R_1)^{-4}}_{\text{zone B}}} = 100 \text{ or } 20 \text{ dB} \qquad \text{(worst case)} \tag{16.1-9}$$

The average C/I received by the desired mobile unit can be calculated by taking the probability that each interfering mobile unit would be located in one of its three zones of an interfering cell. Thus:

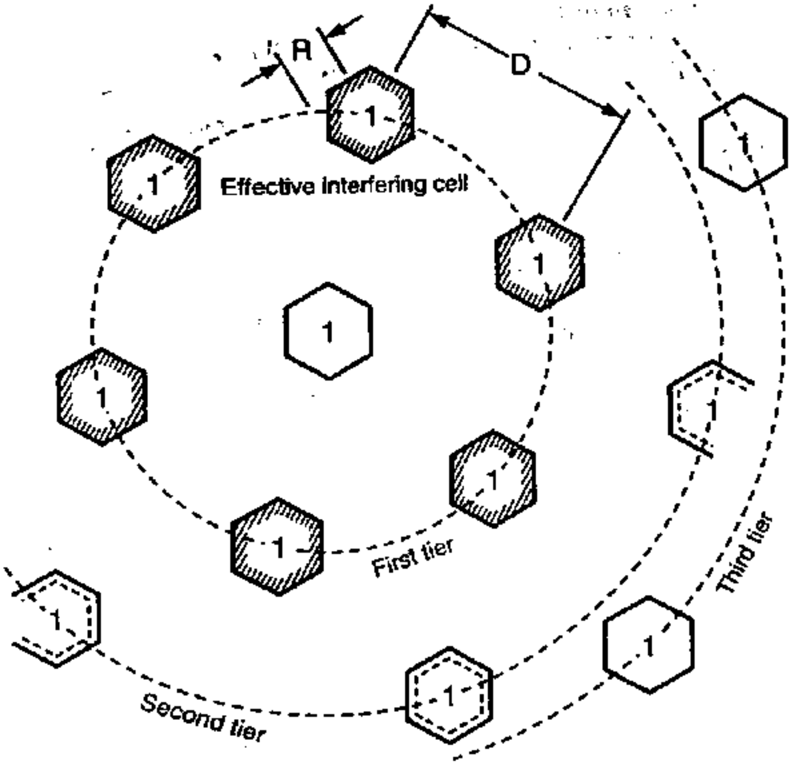


Figure 16.4 Six effective interfering cells of cell 1.

$$C/I = \frac{R^{-4}}{2\left[\frac{2}{3}\left(\frac{13}{2}R_1\right)^{-4} + \frac{1}{3}(4.6R_1)^{-4}\right] + \left[\frac{2}{3}(4.6R_1)^{-4} + \frac{1}{3}(6R_1)^{-4}\right] + 2\left[\frac{2}{3}\left(\frac{13}{2}R_1\right)^{-4} + \frac{1}{3}\left(\frac{16}{2}R_1\right)^{-4}\right] + \left[\frac{1}{3}\left(\frac{13}{2}R_1\right)^{-4} + \frac{2}{3}\left(\frac{16}{2}R_1\right)^{-4}\right]}$$

$$= 193.4 \text{ or } 22.8 \text{ dB} \qquad \text{(average case)} \qquad (16.1\text{-}10)$$

As seen from Eq. (16.1-10), the average C/I almost equals 23 dB, which is 5 dB better than the AMPS voice quality specification. By keeping the minimum $D_1/R_1 = 4.6$ in Fig. 16.3, as a result, the co-channel cell separation D equals $3R$. The value of K can be found from

Eq. (16.1-3) as $K = 3$. The capacity of intelligent microcells is greater than that of AMPS by a factor of 7/3, or 2.33.

Reuse of sectorial beams with directional antennas. Applying the same intelligent cell concept, we use antenna beams to confine the energy to individual mobile units in the cell. In a $K = 7$ cellular system, each cell has a set of M/K frequency channels. At a cell site, if six sectorial (directional) antennas are used to cover 360° in that cell and if the whole set of frequency channels assigned to the cell is divided into two subsets which are alternating from sector to sector, then there are three cochannel sectors using each subset in a cell, as shown in Fig. 16.5. In this arrangement, we can increase the capacity by 3 times. If N sector beams are reused alternately, the capacity is increased by $N/2$ times the AMPS capacity. This reuse of the sectorial beam scheme can be used in a small-cell system or a large flat-terrain cell system with much less reduction on trunking efficiency. Of course, in reality, the directional antenna front-to-back ratio should be considered to avoid unnecessary interference in the cochannel sectors.

Adaptive antenna array.[5] The antenna pattern can be formed by tracking the mobile unit and nulling the interference. Therefore, if the same frequency channel can be used by N mobile units in a cell, the capacity is Nx. Also, because an adaptive antenna array is used, the antenna beam is able to follow the mobile unit, thus reducing interference. The cell reuse configuration may reduce from $K = 7$ to a smaller K depending on the magnitude of N. If N is large, the N antenna beams operating the same frequency to serve N users within a cell can be treated as they are from an omnidirectional antenna. Therefore, $K = 7$ will remain unchanged. If N is confined in a 120° sector, then the required $C/I = 18$ dB can be used to determine the D/R ratio. Since there are only two interfering cells, as shown in Fig. 16.2, the C/I is expressed approximately as

$$C/I = \frac{R^{-4}}{2D^{-4}} = 63 \text{ or } 18 \text{ dB} \qquad (16.1\text{-}11)$$

Solving Eq. (16.1-11) yields

$$D/R = (126)^{1/4} = 3.35$$

The value of K can be obtained from Eq. (16.1-3) as

$$K = \frac{(3.35)^2}{3} = 3.7$$

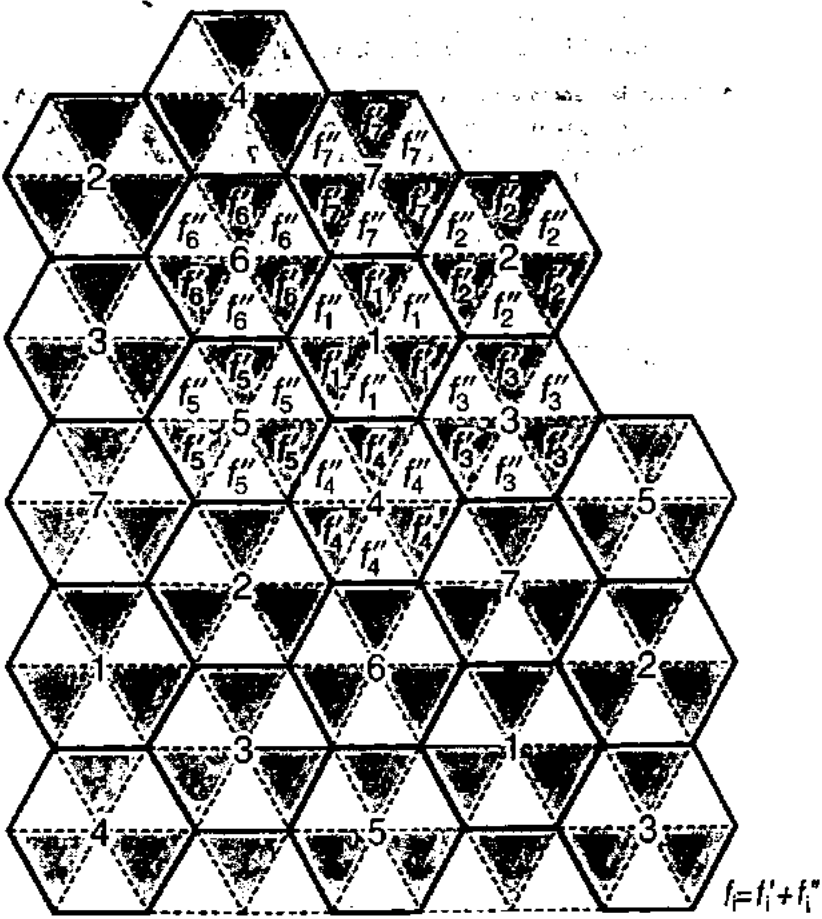


Figure 16.5 Reuse of sectorial beams with directional antennas.

Since the adaptive antenna beam follows the mobile units, cochannel interference is reduced. Also, since sectorization is used, a system with a frequency reuse factor $K = 4$ can be realized.

These adaptive antenna patterns provide a good means of generating multiple cochannel mobile calls on the reverse links. Then with the identical antenna patterns for transmitting and receiving at the cell site, the calls are conducted on the forward links as well. This is because the reciprocity principle works based on Lee's Model,[6] the active region around the mobile unit is defined by a radius of about 100 to 200 wavelengths.[7] The beam angle α received at the cell site is a function of distance R, as shown in Fig. 16.6:

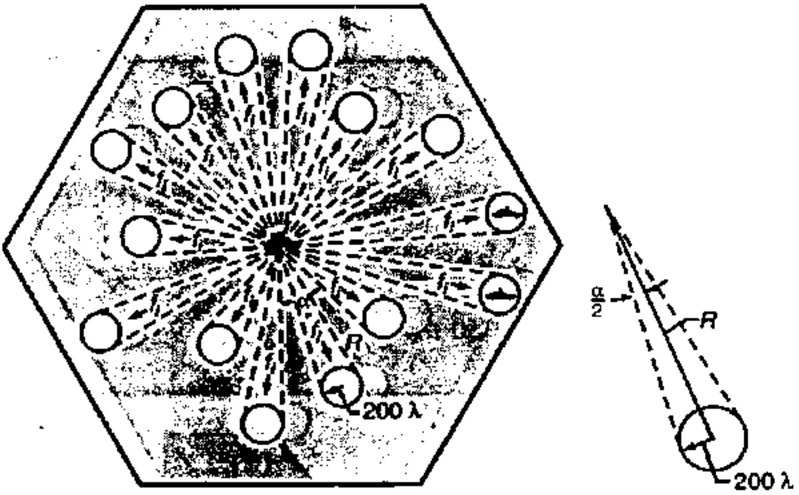


Figure 16.6 Intelligent cell with adaptive antenna-array beams.

$$\alpha = \frac{2 \times 200\lambda}{R} \tag{16.1-12}$$

where λ is the wavelength. Usually operating at UHF, the antenna has a beamwidth θ always larger than α. Then the isolation between the two cochannel mobile calls will be measured by θ, not α. Also, the definition of the antenna beamwidth θ is not based on a 3-dB beamwidth but rather on an 18-dB beamwidth. When the two cochannel mobile units move closer within one θ angle, a handoff is initiated. In some proposed systems, the beam nulling is formed between two mobile units. In this case, the nulling angle measured between two mobile units cannot be less than α.

In-building communication. In-building communication needs sufficient traffic channels, but the radio spectrum is limited. We may apply the intelligent cell concept to solve this problem. The number of traffic channels can be increased by treating each floor of a building as a cell. The penetration loss of a radio signal through a reinforced concrete building wall is about 20 dB, and the signal isolation between two adjacent floors is also 20 dB. Therefore let a group of frequency channels M_1 be assigned to the inbuilding use, those same M_1 channels will be reused in every floor of the building, and also in every floor of neighboring buildings (i.e., passive intelligence), as shown in Fig. 16.7.

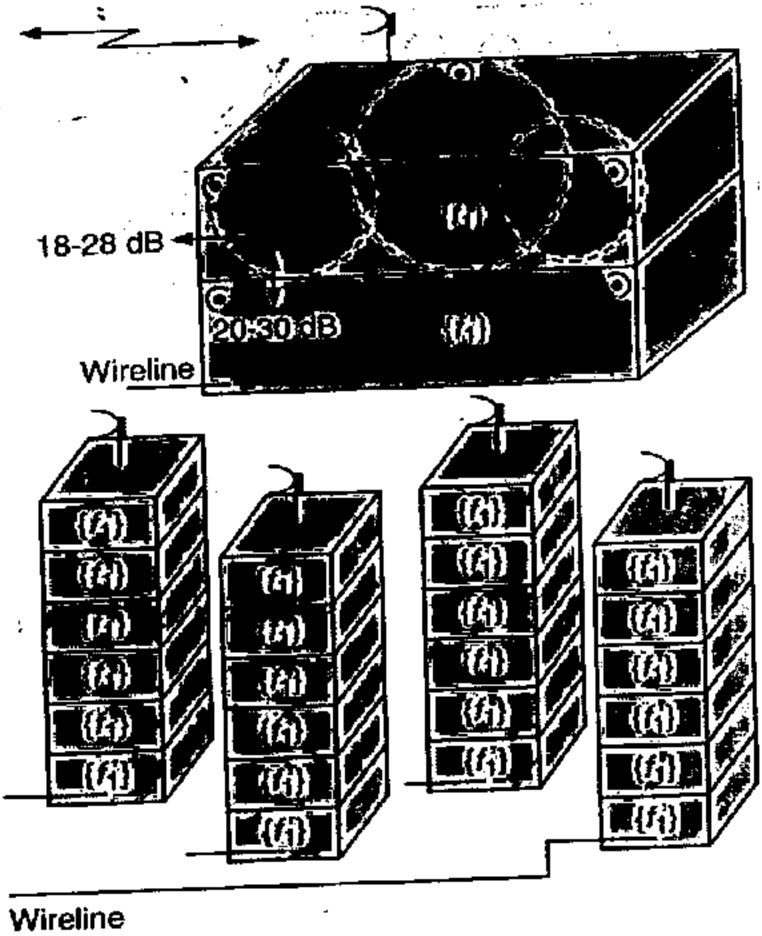


Figure 16.7 Concept of in-building communication.

Because each floor can be treated as one cell, the radio capacity m_1 of in-building communication can be obtained by setting $K = 1$. Then:

$$m_1 = \frac{M_1}{K} = M_1 \qquad \text{number of channels/floor}$$

Now a 20-floor building has $20 \times M_1$ traffic channels. In case interference occurs between two buildings due to the signal penetration of 4 to 6 dB at the window areas, the intelligent microcell cell with N zones can further reduce the interference. Note that the intelligent cell assumes adequate building shielding. When "active" rather than "passive" intelligence is used, buildings with less isolation can still achieve high efficiency of spectral reuse by self-surveying the amount of signal leakage into the building or between floors.

16.1.4 Processing-gain intelligent cells ($K \rightarrow 1$ system)

Philosophy of implementing processing-gain intelligent cells. The concept of the processing-gain intelligent cell can be explained by the analogy of many simultaneous conversations in a big hall (Fig. 16.8). The big hall is just like one big radio channel serving all the traffic in an intelligent cell. The conversations of the different parties are the traffic channels. The processing gain is like the size of the hall, which limits the number of persons, hence, the number of conversations, that can be accommodated. Since all the conversations take place in the hall, the speaker level (power control) of each conversation is the key element in this intelligent cell to keep the interference level in each traffic channel down. Also, if the level of each individual conversation can be controlled intelligently, then we can maintain the total interference level and add more conversations. If the power control is not working, the cell is not an intelligent cell. Then the cell will face the

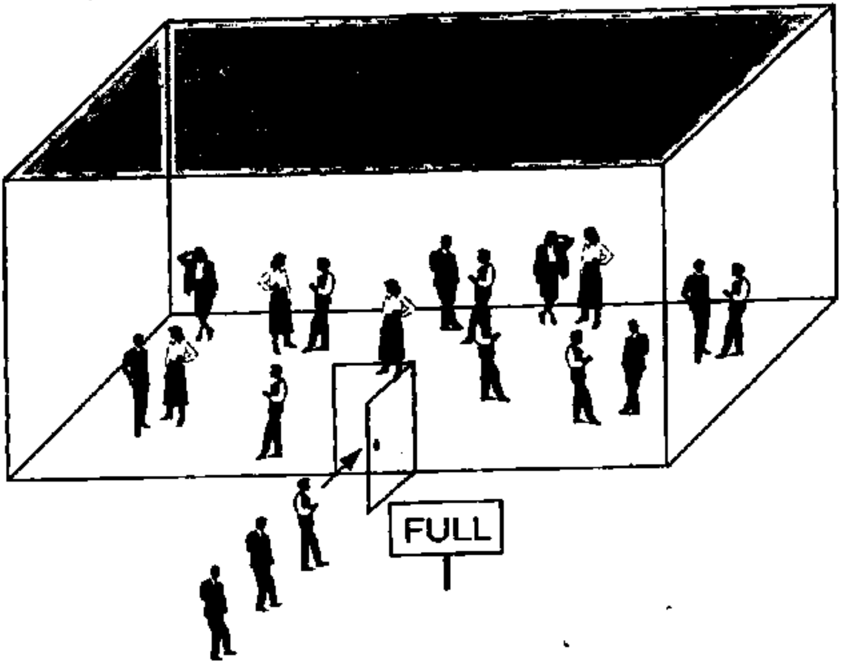


Figure 16.8 Analogy to processing-gain intelligent cell.

cocktail-party syndrome in which no parties can talk except by raising their voices. The processing gain calculation will be shown in the next section.

Direct-sequence CDMA.[8-10] In this code-division multiple-access (CDMA) system, the broadband frequency channel can be reused in every adjacent cell so that K is close to 1, as shown below from our previous definition of Eq. (16.1-3). In a practical sense, D equals $2R$, i.e., all the same available frequencies are used in each cell. Then

$$K = \frac{(D/R)^2}{3} = 1.33 \qquad (16.1\text{-}13)$$

Radio capacity is also based on Eq. (16.1-1). However, in direct-sequence CDMA (DS-CDMA), K is fixed but M (the total number of available channels) is a variable and depends on the interference situation. For the scenario shown in Fig. 16.9, the interference comes

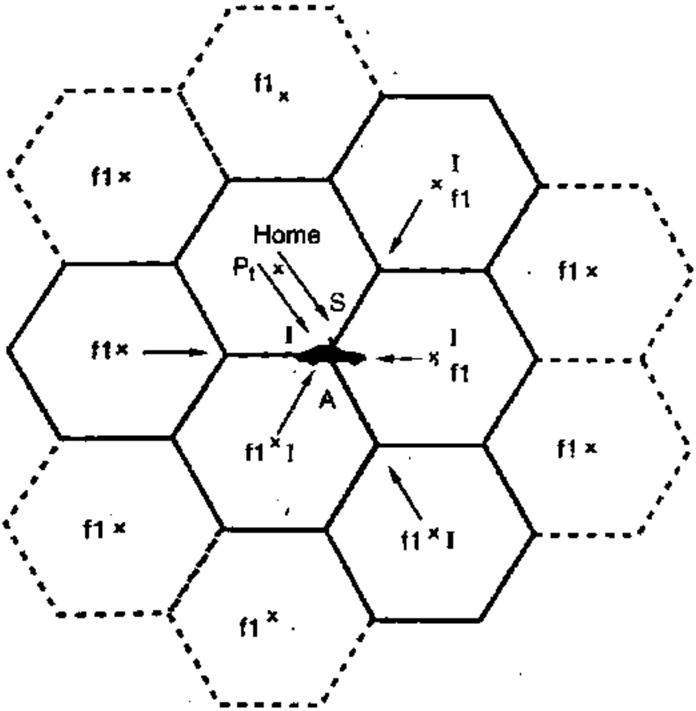


Figure 16.9 CDMA system and its interference (from a forward link scenario).

from the home cell and the adjacent cells and the value of C/I is expressed as

$$\frac{C}{I} = \frac{E_b}{I_0} \times \frac{R_b}{B} = \frac{E_b/I_0}{\mathrm{PG}} \tag{16.1-14}$$

where E_b = energy per bit
I_0 = interference per hertz ($I_0 >> N_0$, where N_0 is thermal noise per hertz)
R_b = information rate
B = bandwidth per channel
PG = processing gain $= 10 \log (B/R_b)$ (16.1-15)

In DS-CDMA, since PG is greater than one, C is always smaller than I in Eq. (16.1-14) even if there is only one active user. The processing gain is used to overcome I and determine the number of traffic channels that can be created.

From two sets of given values, E_b/I_0 and R_b/B, we can find the C/I from Eq. (16.1-14). Then, from the scenario of Fig. 16.9, the C/I at the mobile location A can be used to find the number M which is considered a worst case. Assume that the interference level is much higher than the thermal noise level; then

$$\frac{C}{N+I} \rightarrow \frac{C}{I}$$

Assume that in a DS-CDMA system,[8] $B = 1.23$ MHz and $R_b = 9.6$ kbps. Then PG = 1.23 MHz/9.6 kbps or 21 dB.

In this system, a voice quality is accepted at a frame error rate FER $= 10^{-2}$, which typically corresponds to $E_b/I_0 = 7$ dB. Knowing the values of PG and E_b/I_0, C/I of Eq. (16.1-14) can be obtained:

$$C/I = 7 - 21 = -14 \text{ dB or } 0.03981$$

Find the number of traffic channels m_i in each cell from C/I by:

$$C/I = \frac{\alpha_1(R)^{-4}}{\underbrace{\alpha_1(m_1 - 1)\cdot R^{-4}}_{\text{own cell}} + \underbrace{(\alpha_2 m_2 + \alpha_3 m_3)(R)^{-4}}_{\text{2 adjacent cells}} + \underbrace{\beta\cdot(2R)^{-4}}_{\text{3 interim cells}} + \underbrace{\gamma(2.63R)^{-4}}_{\text{6 distant cells}}}$$

$$= 0.03981 = \frac{1}{25.1}$$

where

$$\beta = \alpha_4 m_4 + \alpha_5 m_5 + \alpha_6 m_6$$

$$\gamma = \sum_{i=7}^{12} \alpha_i m_i \tag{16.1-16}$$

and m_i and α_i are the number of traffic channels and the power level, respectively, in each of the i cells. Solving Eq. (16.1-16), we obtain

$$m_1 = 26.1 - \left[\frac{\alpha_2 m_2 + \alpha_3 m_3}{\alpha_1}\right] - \frac{\beta}{\alpha_1}(2)^{-4} - \frac{\gamma}{\alpha_1}(2.63)^{-4} \tag{16.1-17}$$

Case A. Single cell case ($\alpha_i = 0$ for $i \neq 1$). From Eq. (16.1-17):

$$m_1 = \frac{I}{C} + 1 = 25.1 + 1 = 26.1 \text{ traffic channels/cell}$$

Case B. Identical-cell case. All the cells have the same power and the same number of traffic channels: $m_i = m_j$ and $\alpha_i = \alpha_j$. We may substitute $m_i = m$ and $\alpha_i = \alpha$ into Eq. (16.1-16) or Eq. (16.1-17) and solve for m as follows:

$$26.1 = m[3 + 3 \cdot (2)^4 + 6 \cdot (2.633)^{-4}]$$

$$m = 7.85 \text{ traffic channels/cell}$$

Both traffic channels appearing in Case A and Case B include the overhead channels for sync and set-up, but do not take into consideration the voice activity cycle or sector-reuse factor as used in real commercial systems.[8]

Frequency hopping. A frequency-hopping system can be used as a CDMA system (FH-CDMA). The hopping pattern can be formed as a code sequence. Frequency hopping has been used in the past to overcome enemy jammers in military applications. There are two kinds of hopping, fast frequency hopping and slow frequency hopping.

Slow frequency hopping (SFH) is defined as sending multiple bits on a single hop.[11] Depending on the degree of the enemy's quick reaction, the hopping rate would be adjusted. Fast Frequency Hopping (FFH) is defined as sending a bit on a pseudo-random pattern of frequency channels, then sending the next bit on a different pseudo-random pattern of frequency channels. The multiple frequency channels form a code for one bit which is sent out simultaneously or sequentially. The bandwidth of the channel depends on the transmission bit rate. The scheme of simultaneously sending out the same bit on different frequency channels requires a larger bandwidth for sending each bit. This is another wideband CDMA system. Sending bits over frequency channels sequentially is the conventional FH-CDMA system. The fast frequency hopping CDMA system requires a larger bandwidth than the slow frequency hopping CDMA system. This is because in FFH, one bit requires multiple frequency-hopping channels to be sent out sequentially.

In an FH system, there are two kinds of processing gains. One kind of processing gain is used to measure the power of defeating enemy jammers. It is really focused on minimizing collisions of two carriers occupying a frequency channel at the same time. Then if the desired signal has 1000 channels to hop to avoid the jammer, the processing gain is 30 dB. We can derive this processing gain against jamming from $(C/I)_J$ using Eq. (16.1-14):

$$(C/I)_J = \frac{E_b R_b}{I_0(BN)} \tag{16.1-18}$$

where B is the bandwidth of sending R_b through a single channel (assume that $B = R_b$) and N is the number of available frequency channels to be hopped from. Each channel has the same bandwidth B. The processing gain is

$$\text{PG} = \frac{BN}{R_b} = N \tag{16.1-19}$$

From Eq. (16.1-19) we may conclude that FFH and SFH can take the advantage of the processing gain in defeating enemies.

The other kind of processing gain is used to increase radio capacity. It is focused on spreading energy channels such that the interference seen by each bit is near the minimum acceptable performance threshold. The carrier-to-interference ratio $(C/I)_F$ of a frequency-hopping system can be expressed differently from Eq. (16.1-14) as

$$(C/I)_F = \frac{E_b R_b}{I_0(BF)} = \frac{E_c R_c}{I_0(BF)} \tag{16.1-20}$$

where E_b = energy per bit
R_b = bits per second
E_c = energy per code bit
R_c = number of code bits per second
F = number of frequency channels per bit ($F_b \geq 1$)
B = bandwidth of sending a signal of R_b stream

In a non-FH system or an SFH system, R_c and F are always equal to one because there is no spread spectrum using pseudonoise (PN) coding of the data bits. Then $E_c = E_b$, $F = 1$, and Eq. (16.1-20) becomes Eq. (16.1-14). It has been shown that SFH does not experience processing gain in order to increase radio capacity. The SFH system is more like the Aloha multiple access scheme.[14]

In an FFH system, the processing gain for radio capacity depends on F, the number of frequency channels per bit, as

$$\text{PG} = \frac{BF}{R_b} = F \tag{16.1-21}$$

Assume that the information rate R_b is 10 kbps and one bit hops among 100 frequencies, $F = 100$, then the total bandwidth required is $BF = 1$ MHz.

Impulses in time domain.[12-13] We may create a spread spectrum system based on impulse position modulation in the time domain. The C_p/I can be obtained as

$$C_p/I = \frac{E_p P_b R_s}{I_0 B} \tag{16.1-22}$$

where C_p = carrier power of data stream
E_p = energy per pulse
P_b = number of pulses/bit
R_s = number of bits/s

If $P_b = 1$ then $E_p P_b = E_b$ and Eq. (16.1-22) becomes Eq. (16.1-13). If $P_b > 1$, the impulse position modulation system becomes a spread spectrum system.

The same principle of using DS-CDMA for increasing cellular capacity can be applied to impulse position modulation. When the pulse width of an impulse is less than 1 ns, the advantage of applying impulse position modulation starts to show.

16.1.5 Summary of intelligent cell approaches

The intelligent cell can be described in two ways: (1) it intelligently delivers the signal to the mobile unit; (2) it ensures that the signal indestructibly resides with the interference. Several different methods of increasing traffic capacity by using the intelligent cell concept have been mentioned. These methods are very important for PCSs. Among the methods of forming a power-delivery intelligent cell, the sectorial cells may increase capacity if the cell reuse factor K decreases. Frequency reuse with multiple antenna beams and the microcell with multiple zones apply the intelligent cell concept and can also increase capacity. The method of forming a power delivery intelligent cell can be applied to FDMA and TDMA[15] systems. Among the methods of forming a processing-gain cell, both direct-sequence CDMA[16] and FFH can increase capacity because of their processing gain but SHF cannot.

In a conceptual case, we can narrow the beamwidth θ of an antenna pointing at the mobile unit to a limit; i.e., θ becomes narrower and narrower until $\theta \rightarrow 0$ (Fig. 16.10). This is the best case for eliminating interference. When $\theta \rightarrow 0$, the wireless line is just like a wire line. Therefore, we conclude that the wire line is the least interference link for the wireless link. If a wire line could be replaced by a wireless line with $\theta \rightarrow 0°$, then no radio interference exists. As a result, no limitation in increasing the number of channels has imposed by any radio interference among them.

After learning the capacity issues of the three multiple-access schemes, we may present them in three axes, number of frequency channels (*x*), number of time slots (*y*), and number of code sequences (*z*), as shown in Fig. 16-11*a*. The shaded regions represent the utilization of the spectrum. The larger the region, the higher the spectrum efficiency. Three subcases, FDMA, TDMA, and CDMA, appear in Fig. 16.11*b*, *c*, and *d*, respectively. The shaded regions in each subcase indicate the degree of spectrum efficiency. There is a different representation of spectrum efficiency in each multiple-access scheme.

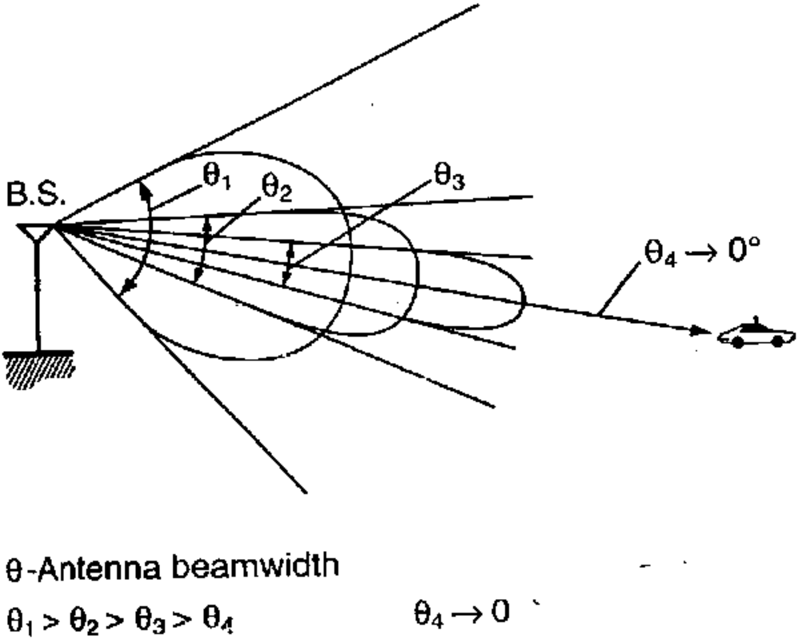
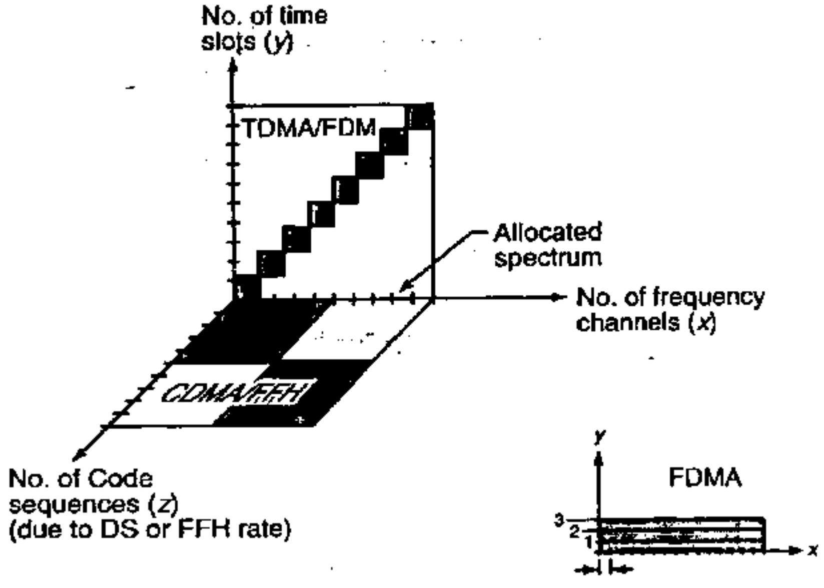


Figure 16.10 The best case of delivering power to the mobile unit in space by antenna.



(a) General Representation (b)

Figure 16.11 Spectrum efficiency representation.

Therefore, the bottom line of the intelligent cell is either to allow no interference to exist during signal reception or to let the signal tolerate a great deal of interference while it is being received.

16.2 Applications of Intelligent[17,18] Microcell Systems

16.2.1 Description of the intelligent microcell operation

An intelligent microcell system was described in Sec. 16.13. This system can be applied to analog and digital systems. To show the improvement over AMPS provided by intelligent microcells, the voice quality is 2 dB better and the capacity increases more than 2 times. The microcell system is shown in Fig. 16.12. The base-site equipment can be located at one zone site or at any remote place. The base site stores a zone selector, a scanning receiver, and a set of radio channels (Fig. 16.12*a*). The microcell system can be attached to a regular macrocell site (could be a different cellular vendor's equipment), and can be used without any modification on the base-site controller. Also, the microcell system can operate alone if the controller is replaced with an independent microprocessor. Either has to connect to the MTSO.

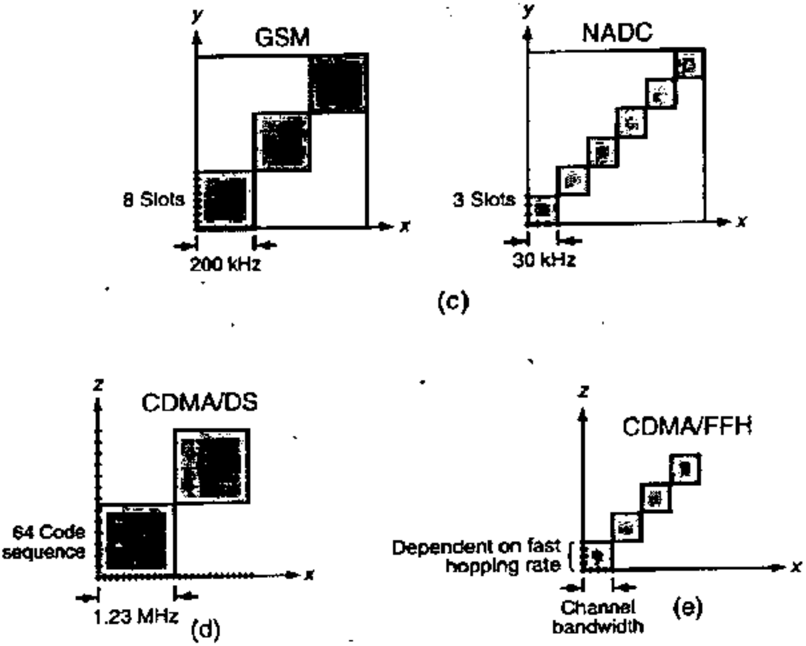


Figure 16.11 (*Continued*)

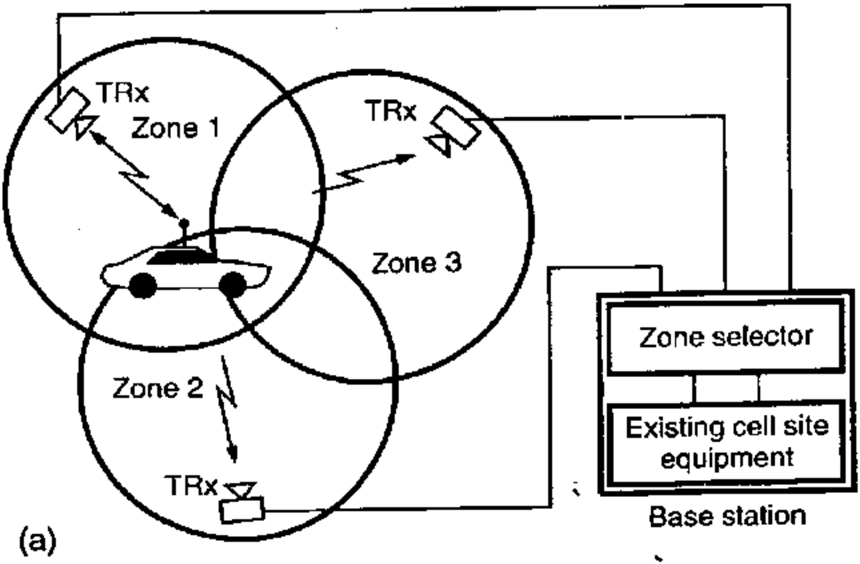


Figure 16.12 The structure of the microcell system. (*a*) The basic microcell concept; (*b*) modifying the equipment arrangement for the microcell system.

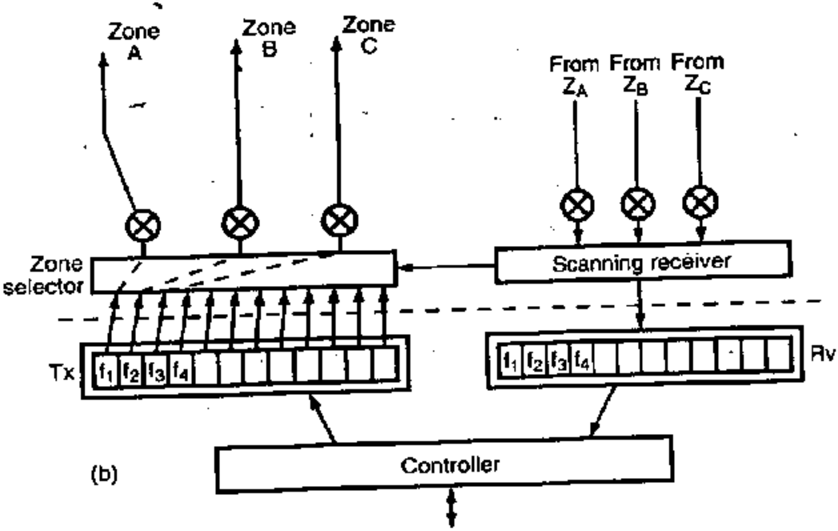


Figure 16.12 (*Continued*)

If the mobile unit is in zone 1, the scanning receiver detects the signal received from zone 1 that is the strongest, then directs the zone selector to switch to zone 1 through a pair of converters (called *translators*). All three zones are receiving the same signal on the same radio channel at any time but only one zone is chosen to transmit the signal. The equipment arrangement for the microcell system at the base site is shown in Fig. 16.12*b*. In this figure, the new components—zone selector, scanning receiver, and converters—above the dotted line are installed to replace the old components such as power amplifiers, combiner, and 800-MHz antennas.

System elements

Converters. There are three pairs of converters in the three-zone microcell system. Each pair is used to connect the signals from the base site to the designated zone site. The converter (Fig. 16.12*b*) is a broadband device which can upconvert signals before transmitting them, then downconvert signals while receiving them. There are two kinds of converters: microwave and optical-fiber. The microwave type can use different upconverting microwave frequencies, such as 18, 23, or 40 GHz. The higher the frequency, the shorter the reception range. The optical-fiber type is used for upconverting the signal to optical frequency and sending it over fiber cable. Every converter is associated with an amplifier for the weak signals after downconverting back to the cellular frequencies. A converter can carry an average of 20 to 30 cellular channels, depending on the linear range of the converter. In this case, on average, if each zone site will take 20 mobile calls, the total of three zones will have 60 mobile calls. The converters[19] can be either analog or digital regardless of whether the system is analog or digital.

At any zone site, only one converter is needed, as shown in Fig. 16.12. The zone site can physically represent a regular cell site. The converter can be mounted on a utility pole or light pole (Fig. 16.13). Therefore, the size of converters becomes a more important factor for the zone site. The smaller, the lighter, the better.

Scanning receiver. The scanning receiver will scan three zone sites for each frequency. After scanning all the frequencies sequentially, the receiver goes back to the first frequency. The required time of scanning

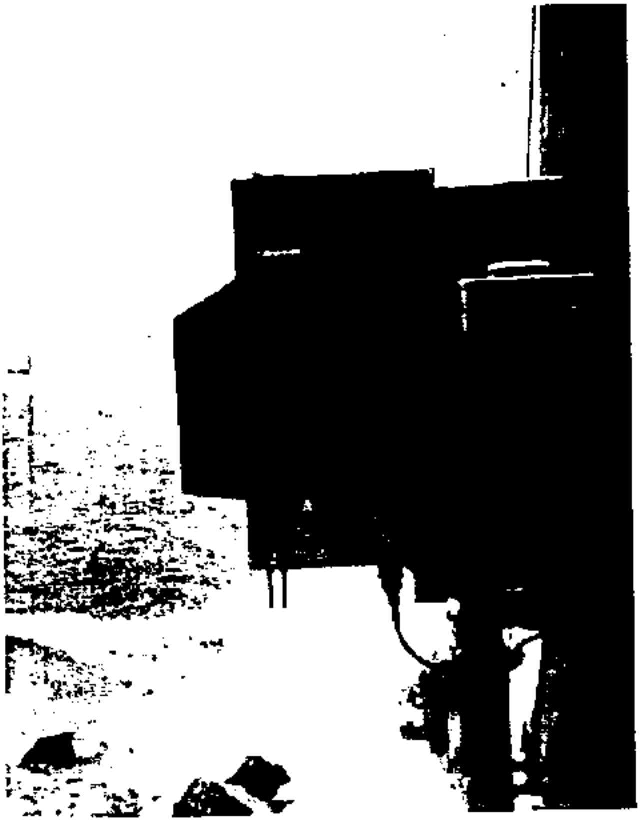


Figure 16.13 An optical converter (analog conversion) manufactured by Allen Telecomm.

the frequencies and zones is critical. The required time of scanning needs to be short so that more frequencies can be scanned by one scanning receiver.

A scanning receiver for a TDMA system should have the ability to scan not only the frequencies, but also the zones and the time slots. Therefore, a time multiplexing device should be associated with the scanning receiver.

Zone selector. A zone selector is a single switch. It usually switches a signal from one zone to another zone in less than a microsecond. Therefore, no data stream will be affected by this fast switch. In TDMA, the zone selector is able to switch a signal in one time slot of one zone to a designated time slot of another zone.

Areas of application. The intelligent microcell has five applications.

1. *Delivering to extended cells.* Converters can be used to deliver the 800-MHz signal from the base to an extended cell by upconverting the signal to a new frequency for transmission through the air, then downconverting to 800 MHz when the signal reaches a cell where only a converter is installed (Fig. 16.14).
2. *Increasing capacity.* Since the power can be delivered and received intelligently at the mobile unit, the capacity increases.

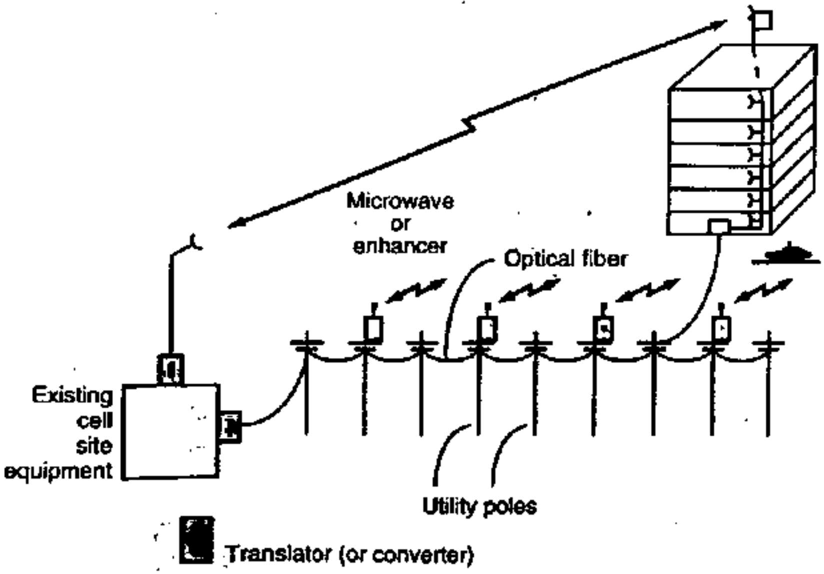


Figure 16.14 Microcell delivery system. The translators are used to upconvert an 900-MHz GSM signal to an optical signal (or microwave signal) and downconvert an optical signal (or microwave signal) to 900 MHz.

3. *Coverage.* In some areas, the government will not allow regular cell sites to be installed. Under those circumstances, these invisible zone sites can be used to provide the coverage especially in urban areas.[20–22]
4. *Reducing interference.* At some high cell sites, the generated interference to the other low sites becomes a problem. An intelligent microcell can reduce its unnecessary radiated power and the interference it generates.
5. *In-building communication.* The intelligent cell can increase radio capacity many times. A description of this application will appear later.

Advantage of implementing intelligent cells

1. Any number of zones can be included in a microcell. More zones in a microcell can further reduce power and lower the interference.

2. The antennas face inward from the edges of the cell, rather than outward, further reducing the interference.

3. All the zone-site receivers actively receive mobile or portable calls on all frequencies. Since a portable unit's transmit power is usually low, a single cell site receiver has difficulty accepting and maintaining a call, but with three zone sites receiving the same signal from the portable, the reception is much improved. Thus an intelligent microcell is well-suited for PCS terminals.

4. Within a three-zone microcell, no handoff is needed. This arrangement eases the load of switches (MTSO) because of fewer handoffs, and the switches can have more capacity to handle new calls. By reducing handoffs, the intelligent microcell also reduces the number of calls dropped during attempted handoff. In a conventional microcell system, the vehicle often leaves the cell before the handoff action can be completed.

5. The system can be implemented on any existing cellular system. The modification is shown in Fig. 16.12*b*, where a dashed line divides the equipment in a regular cell site from that in a microcell site. Where the power amplifier and channel combiner would be installed in a regular cell site, the scanning receiver, zone selector and the converter are installed instead in a microcell site.

6. The zone site can be moved from one location to another in almost no time. To take an antenna and a converter down from one utility pole and put them up on another utility pole is easy.

7. A fiber-cable network can provide redundancy of connections. If the fiber cable is broken on one end, the signal can be delivered via the network through the other end to the mobile unit.

8. No need to modify the existing cellular subscriber units for the intelligent microcell system.

9. Better voice quality than an analog cellular system.

10. Higher capacity—can be 2.33 times the capacity of the analog system.

Cable cost and converter quality. In high traffic congestion areas, many zone sites will be installed. The major cost of providing the fiber links is the installation of fiber cable. Usually, the initial cost of the fiber links is high. This situation may lead us to recall that in the beginning of this century many people complained that the initial cost of telephone-wire installation was too high. One hundred years later, we are all benefiting from this telephone network. Since the fiber-cable network will inevitably be the future broadband network, why should we have to be concerned about the initial costs of the installation if it is needed for the future?

The quality of converters is a big challenge. The simplest way of building a converter is to use an analog direct conversion approach. But the required linearity over a broad dynamic range with broadband conversion could make a high-quality analog converter difficult to realize. A digital converter may cost more but may not require linearity, therefore the quality can be better. However, the analog converter would gracefully degrade in performance, but the digital converter would sharply degrade.

16.2.2 Applications to increasing capacity

To verify the increased capacity provided by intelligent microcells, four microcells were deployed in West Los Angeles. Each microcell had three zone sites. The cell reuse pattern was $K = 3$ (Fig. 16.15). Cells 1A and 2B were the cochannel microcells. The measured signal strengths at 1A and 2B are shown in Fig. 16.16*a* and *b* respectively. From the measured data, we could calculate the C/I at zone 1A and at zone 2B, as shown in Fig. 16.16*c*. The result indicates that C/I at each cochannel microcell (1A or 2B) is about 20 dB, as we have expected. Since the cell reuse factor K reduces from $K = 7$ to $K = 3$ while the C/I improves from 18 dB to 20 dB, both the capacity and the voice quality agree with the theoretical prediction.

Deployment along city streets. Deploying intelligent microcells along city streets is depicted in Fig. 16.17. All the zone sites are located at street crossings. They are lined up diagonally, as shown in the figure. Since each zone site transmits low power, only enough to cover two crossed streets, we may connect the four zone sites to form a microcell

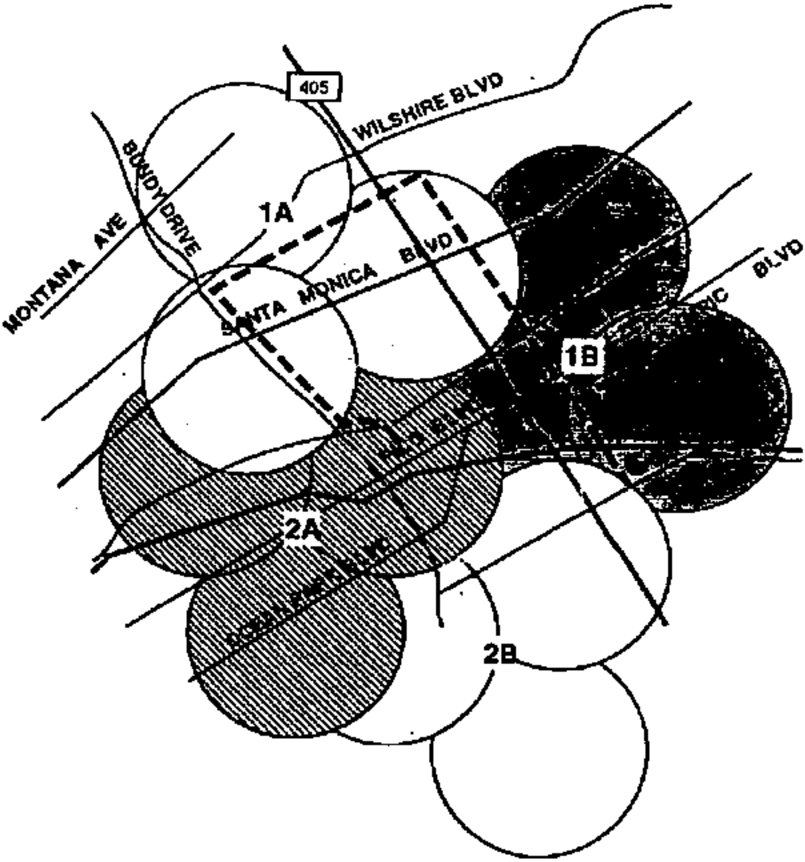
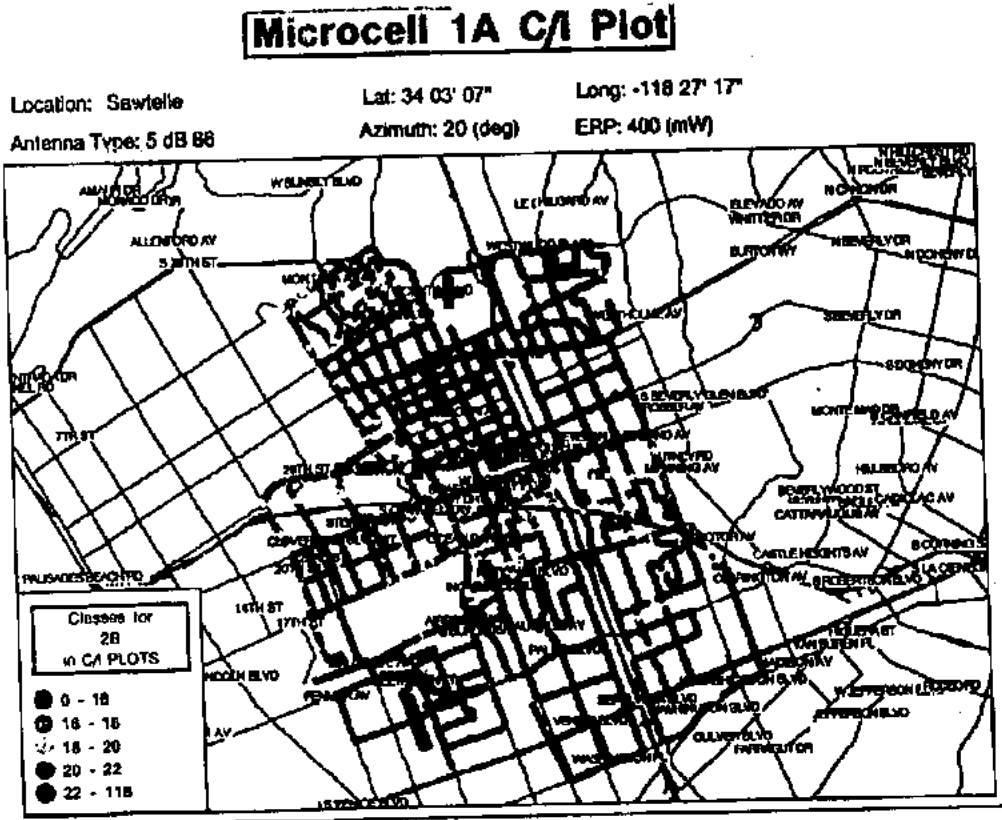


Figure 16.15 Four-microcell pattern and fiber-optic backbone.

using one zone selector. Then, when a vehicle is assigned to one frequency channel f_i, this f_i will be switched from one zone site to another zone site, depending on the zone where the mobile unit is. If the zone selector can serve 20 mobile calls at one time, the same number of calls will be served in this four-zone microcell. For this low-power, intelligent power delivery approach, all the cochannel microcells can be pulled closer. As a result, the capacity is increased.

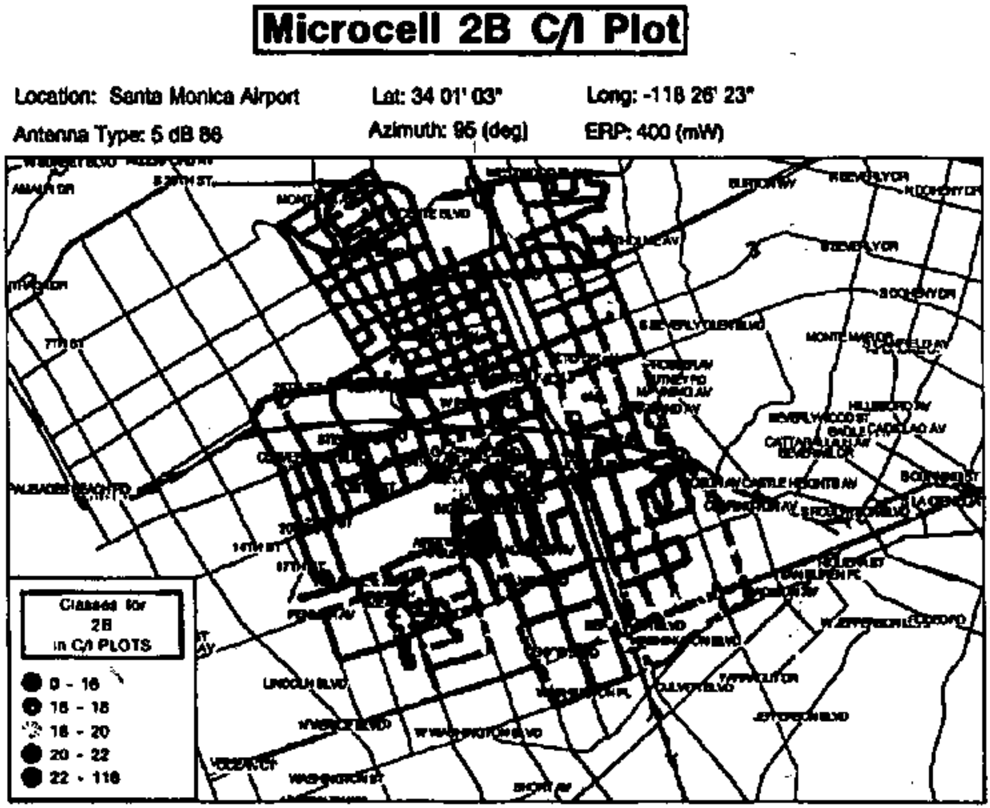
16.2.3 Applications of coverage provision

There are two applications of the coverage provision: coverage along winding roads and coverage under the ground.



(a)

Figure 16.16 (*a*) Microcell 1A C/I plot (measured). (*b*) Microcell 2B C/I plot (measured). (*c*) Microcell C/I plot (calculated).


Microcell 2B C/I Plot
Location: Santa Monica Airport
Lat: 34 01' 03"
Long: -118 26' 23"
Antenna Type: 5 dB 86
Azimuth: 95 (deg)
ERP: 400 (mW)
Classes for
2B
in C/I PLOTS
0 - 16
16 - 18
18 - 20
20 - 22
22 - 116
AMALFI DR
S 26TH ST
BURTON WY
S BEVERLY DR
7TH ST
S BEVERLY GLEN BLVD
MONTE MAR DR
HILLSBORO AV
CADILLAC AV
CASTLE HEIGHTS AV
LA CIENEGA
14TH ST
17TH ST
PENMAR AV
LINCOLN BLVD
W JEFFERSON BLVD
JEFFERSON BLVD
W WASHINGTON BLVD
WASHINGTON ST
SHORT AV

(b)

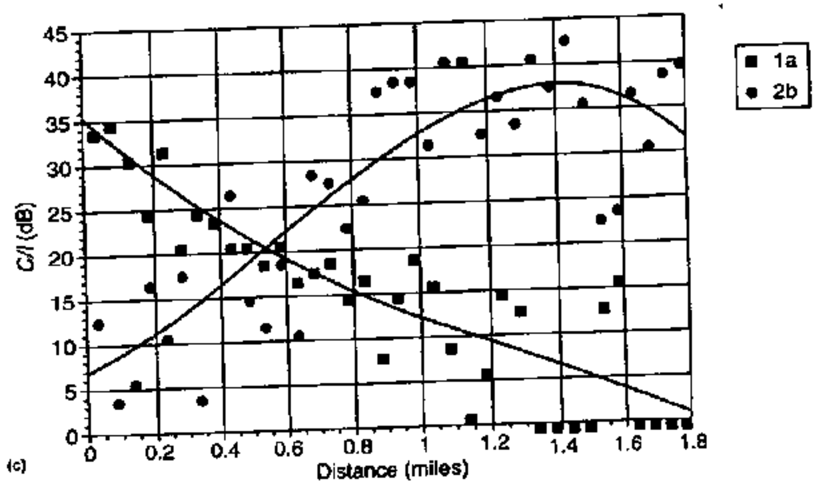


Figure 16.16 *(Continued)*

Coverage along winding roads. Roads like the Pacific Coast Highway, in Malibu, or the road along Santiago Canyon, in Los Angeles, need coverage that stretches up to 15 mi. In Malibu, the zoning requlations prevent the installation of regular cell sites. In Santiago Canyon, the regular cells installed along the winding roads need to be very close for coverage and as a result are very costly. For these reasons, intel-

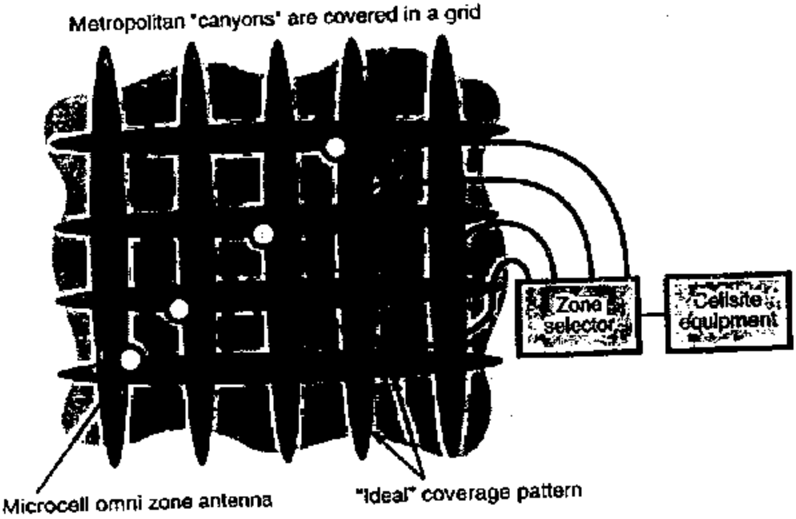


Figure 16.17 Metro "canyon" coverage.

ligent microcells are a good candidate in both cases. In Fig. 16.18, two directional antennas back-to-back are installed on each zone site. Directional antennas and the converters mounted on utility poles form a zone site. Since the traffic is light along these roads, we may use one zone selector in the 15-mi microcell system. Along the road, we number the zone sites along the road 1, 2, 3, 1, 2, 3, repeatedly. In the three-zone selector, all zone sites named zone 1 are connected together, all named zone 2 are connected together, and all named zone 3 are connected together. Then, when a vehicle has been assigned a frequency, f_i and starts to travel from the left end of the road, the left directional antenna of zone 1 receives the mobile signal first, then the right directional antenna on zone 1 receives it later. During this period, all zone 1 sites are on. Because the interference caused by the low-power sites is low, interference is not a concern. The mobile call then passes from zone 1 to zone 2 to zone 3, then back to zone 1 to zone 2 to zone 3, etc. The frequency f_i always stays with this particular mobile call along the 15-mi-long road. No handoff action is needed. This arrangement is suitable for light traffic road conditions.

Coverage under the ground (subway coverage). The intelligent microcell also can be used in subways. In a subway, no interference occurs from the ground cell sites. The three-zone selector can be used to cover a microcell with three subway stations when the stations are very closely separated. Each of the three zones is covered in a different shade pattern in Fig. 16.19. The left-bound train (top) and the right-bound train (bottom) are shared by one zone but covered in different sections. In this case, the two trains stopping at the station will be carried by different zones to ease the traffic.

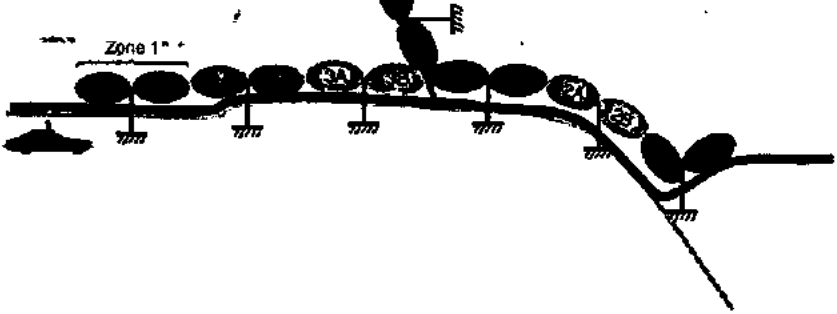


Figure 16.18 Linear coverage concept with directional antennas.

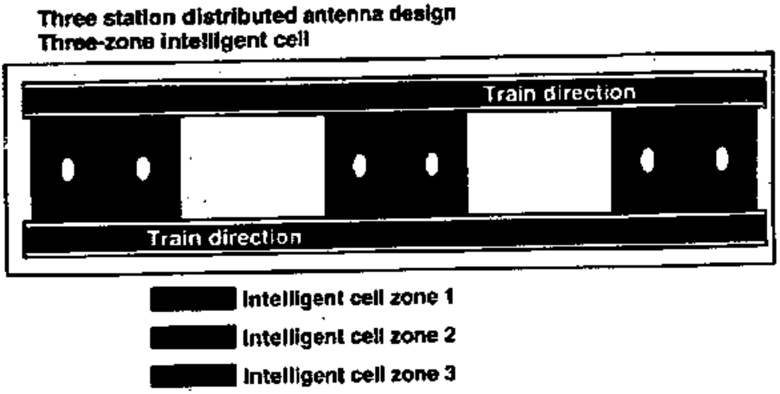

Three station distributed antenna design
Three-zone intelligent cell

Figure 16.18 Underground communication system.

16.3 In-building Communication

16.3.1 Differences between ground mobile and in-building design

There are many good system design tools which have been developed solely for ground mobile cellular systems. However, no proper design tools have been developed for both ground mobile communications and in-building communications operated within one cellular system. As cellular systems are operated today, in-building communication is provided by transmitting radio signals from cell sites so that they penetrate the building walls to reach portable handsets inside buildings. Several difficulties are raised:

1. The transmitted power for in-building communications has to be about 20 dB stronger than that for the ground mobile communications in order to penetrate into or out from a building. Since the maximum transmit power of a portable handset is 8 dB lower than the maximum power of a ground mobile unit, in-building communication is harder to perform on the reverse link (portable-to-base link) than the forward link.
2. The coverage of portable units is not two-dimensional but three-dimensional. Weak reception of portable units is found on lower floors of a building, but strong reception is found on higher floors. This fact presents a difficult condition for running a system which can serve both ground mobile and in-building communication simultaneously.

3. When a radio channel penetrates from outside into a multifloor building, this particular channel can serve only one user who is located on one floor. The other potential users on different floors cannot use the same channel.
4. In-building communiction needs enormous radio channels which the current cellular system cannot provide.

16.3.2 Natural in-building radio environment

Building penetration. The signal penetrating through the building wall is called the *building penetration*. Building penetration studies have shown that penetration loss depends on geographical areas: 22–28 dB in Tokyo, 18–22 dB in Los Angeles, and 13–17 dB in Chicago. The differences are due to the building's construction. Earthquake resistance is the main factor in constructing buildings in some areas. In earthquake areas, the steel frame of a building is built as a mesh-type structure to resist the vibration of the earthquake. The mesh-type structure causes high penetration loss.

Building height effect. Signal reception is always stronger when the cellular handset is at a higher floor. The floor-height gain is about 2.70 dB/floor, independent of the building construction. In Chicago, the reception on the sixth floor is the same as that on the outside ground level. In Tokyo, with its higher penetration loss because of antiearthquake construction, the reception on the eleventh floor is the same as that on the outside ground level.

Building floor isolation. The signal isolation between floors in a multifloor building is on the average about 20 dB. Within a floor of 150 × 150 feet, the propagation loss due to interior walls, depending on the wall materials, is about 20 dB between the strong and weak areas.

16.3.3 A new in-building communication system

Philosophy of designing a new in-building communication system. After studying the natural in-building radio environment, we found that the building structure is a natural radio shield (Fig. 16.20). Therefore utilizing the shielding advantage is the best policy. This means that a signal should not be forced to penetrate into a building with a high-

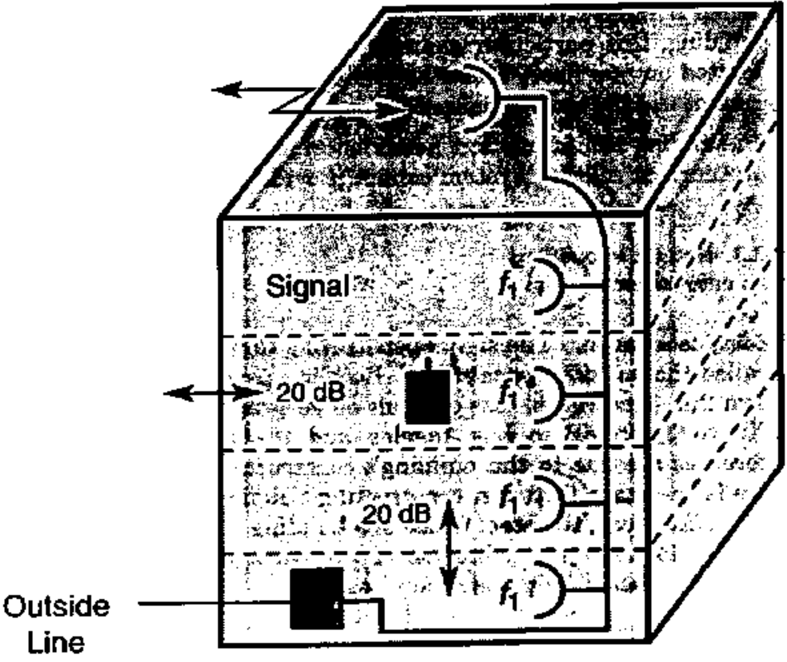


Figure 16.20 Signal within a building.

power radio wave; rather, the signal should be led into the building and distributed onto each floor.

Means of leading the cellular signal into the building. In a cellular system, cellular radios do not need to reside in each building, but rather may be installed in a remote base (Fig. 16.21). This deployment would change the conventional structure of the cell cites and make all the cell sites miniaturized zone sites. There are three methods by which the cellular signal can be led into buildings:

1. Upconvert all cellular signal channels to optical frequency at the base and transmit over optical fibers. When the optical signal reaches the building, downconvert it back to the cellular signals and serve the building users.
2. Upconvert all cellular signal channels to microwave frequency at the base and transmit over a radio link. When the microwave signal reaches the building, downconvert it back to the cellular signals and serve the building users.

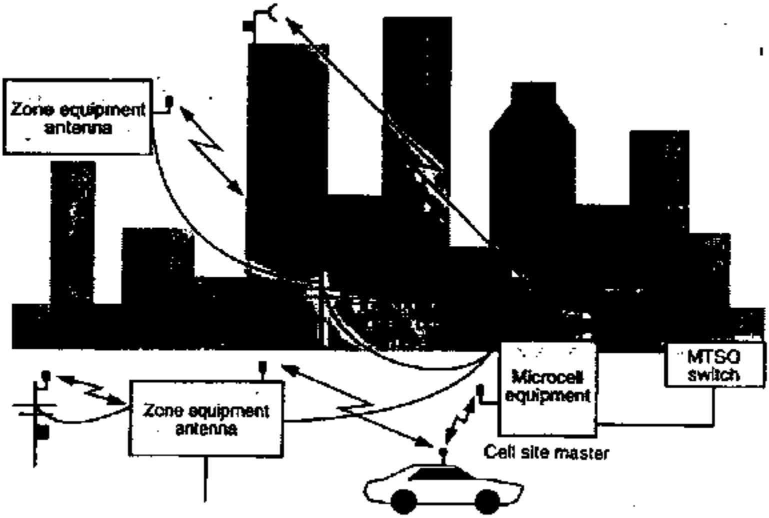


Figure 16.21 Microcell installation concept.

3. Downconvert all cellular signal channels to a 200-MHz UHF signal at the base and transmit it over the cable with low path loss. When the 200-MHz UHF signal reaches the building, upconvert it back to the cellular signals and serve the building users.

16.3.4 In-building system configuration

An in-building system configuration that uses both the natural shielding of the building structure, and a means of leading the cellular signal into the building is illustrated in Fig. 16.7. Calls are sent into the building at upconverted (or downconverted) frequencies to different floors. These lead-in frequencies are converted back to the cellular frequencies as soon as they reach the desired floors.

For a ten-floor building, the same cellular frequency can carry 10 different calls on each of the 10 floors. The capacity is increased 10 times. Also, because of the penetration loss, the same cellular frequencies can be used in neighboring buildings, as shown in Fig. 16.7. Thus the same frequency can be reused many times, and the spectrum utilization is very efficient.

If the building penetration is high, the neighboring buildings will not have cochannel interference. In this case, we can use the intelligent microcell configuration.[2] Each floor will be divided into three or four zones. Only one zone's transmitter is on—the zone where the user is located. Thus the transmitted power is greatly reduced. Within one floor, the user's assigned cellular frequency does not change during the call. The active zone will change, following the location of the user.

If 30 channels are assigned for the in-building users, then the analog cellular system outside the building can still have 365 cellular channel frequencies. These 30 in-building cellular frequencies can generate thousands of calls in an in-building communication system at any time.

Since 30 channel frequencies are designated for the in-building communication only, there is no interference between ground mobile communication and in-building communication. These 30 channel frequencies can be freely reused on each floor in each building without worrying about interference problems with ground mobile communication.

Since the in-building communication in each building can be assigned a station identification (SID) number or the same SID number can be used in all buildings, then the same portable unit can be used for both in-building and the ground mobile communication. The handoff process can be carried out between two communication systems. It would be a benefit to the end user to be able to carry only one portable unit but operate in two systems, the in-building and the ground mobile communication systems.

Handoff between floors can be implemented by assigning a few different channel frequencies from the in-building frequencies to the elevator areas. The handoff will take place by assigning a new elevator area frequency to replace the in-building frequency when the user enters the elevator, and will be handed back to one of the in-building frequencies after the user reaches another floor.

A detailed diagram of an in-building communication system is shown in Fig. 16.22.

16.3.5 A PCS application

Most wireless operators try to divide the market into many segments. Each segment may have many systems in operation such as cellular, in-building, cordless phones, and many others. Each system has to operate its own subscriber units. Thus, there will be many different types of PCS units on the market. However, users (subscribers) want to carry only one portable unit that is small and lightweight and provides long talk time. In addition, they want a PCS that sends out and delivers calls anywhere, anytime.

The new in-building communication system described in Sec. 16.3.4 can meet the end user's needs. It can be used underground, in subways

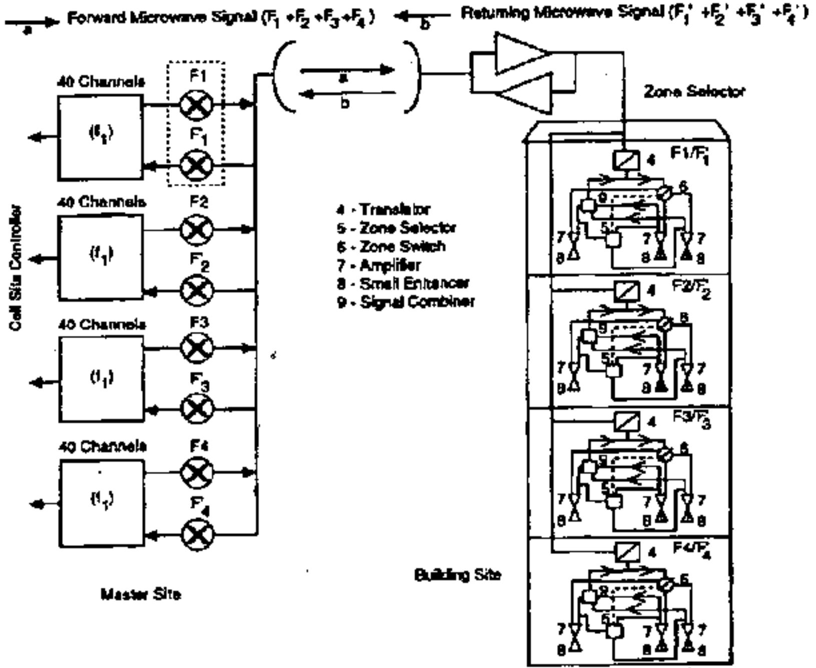


Figure 16.22 A proposed in-building wireless system.

and tunnels. It is a complementary system to the ground mobile macrocell system.

The future PCS unit. The size and weight of today's cellular portable unit are determined by three factors:

1. The size of human fingers is the limiting factor for the size of keypad (or keyboard).
2. The size of the battery is the limiting factor for long radio path communication and long talk time.
3. The length from the mouth to the ear is the limiting factor for the length of the unit.

Today, voice-activated technology is available to replace the dialing process. A memory device in the unit can have the telephone number recorded by voice to correspond to a person's name. Once the person's name is voiced in to the memory, the corresponding telephone number will be sent out. In this case, not only is no keypad needed, but also the caller does not have to remember the number.

The transmitted power of a portable unit can be drastically reduced by implementing the new in-building communication system. The antenna (probe) is located in each floor, thus the transmitted power required to reach the floor antenna from the portable unit can be a fraction of a milliwatt. Furthermore, with an intelligent microcell configuration on each floor, the transmitted power can be further reduced. Therefore, only a tiny battery is needed. The length between the ear and the mouth also can be shortened by using acoustic vibration to transfer the voice from the mouth via muscle to the ear area. Thus both the earphone and the microphone can be located at the ear.

All the above-mentioned technologies are in existence now. Therefore, soon the size of PCS subscribers' units could be as small as a mechanical pencil (Fig. 16.23). A short simple message display will be attached to the pencil-like PCS unit, as in today's pager. A pocket-sized miniprinter can be carried for lengthier messages. A long message can be printed out in an office by downloading the information from the unit's memory.

Future concerns. We have shown that the building is a natural shield for radio interference. Also, cellular frequency reuse in each floor and in the neighboring buildings has shown great spectral efficiency. The new in-building communication system is compatible with the existing cellular system and could be a PCS system in the future.

As far as the future PCS in concerned, we may have to explore the two areas shown is Fig. 16.24, intelligent network and radio access.

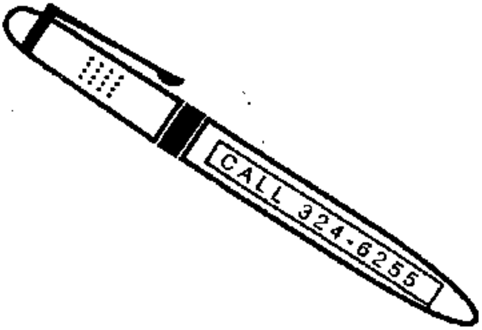


Figure 16.23 A future PCS unit.

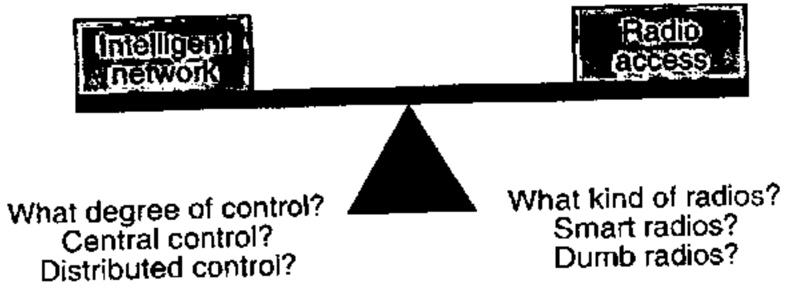


Figure 16.24 Future thinking.

We have to decide whether the intelligent network (IN) should be a central control system or distributed control system. As for radio access, what kind of PCS radio should we have, smart or dumb? If the decision is to use a smart radio, what degree of smartness should the radio have?

16.4 CDMA Cellular Radio Network

16.4.1 System design philosophy

Deploying CDMA systems is like tuning a sophisticated automobile engine. When proper tuning is done, the engine runs very smoothly. But a sophisticated automobile engine needs a sophisticated, computer-aided tuning device, just as a CDMA system needs a computer-aided design tool. As we know, in analog and TDMA systems, capacity increases are a result of the elimination of interference from the desired signal. The signal level of a desired signal is always much stronger than the interference level, say 18 dB or better, for AMPS. However, in a CDMA system, the capacity increase is based on how much interference the desired signal can tolerate. The signal level of a desired signal is always below the interference level. Also, all the users have to share the same radio channel. If one user takes more power than it needs, then the others will suffer and system capacity will be reduced. This scenario is the same as dining in a formal restaurant. The volume of the conversations at every table is low. Therefore, no walls are needed between tables. The guests never feel their conversations are being interrupted by the next table. Therefore, many conversations can occur in the same dining room. This is the concept of CDMA—that all the voice channels are sharing one big radio channel. If people at one table start to raise their voices, the rest of the tables have to either leave or raise their voices too. The former case destroys CDMA. The latter is the so-called cocktail party syndrome which reduces the capacity of CDMA. Neither one is desired. This section addresses how to tune the CDMA cellular radio network in order to tolerate interference.

Designing a uniform CDMA system is comparatively simple. Uniform CDMA means all the cells will be assigned the same number of channels. However, in reality, CDMA systems are not uniform. The voice channels of each cell in a CDMA system are not the same. Because of demographic needs, some cells have more voice channels and some have fewer. Since CDMA has only one radio channel, to generate different voice channels on demand from a single CDMA radio is a big challenge. We would like to describe the challenges by illustrating the design aspects of a CDMA system.

16.4.2 Key elements in designing[23] a CDMA system

The design of a CDMA system is much more complex than the design of a TDMA system. In analog and TDMA systems, the most important key element is C/I. There are two different kinds of C/I. One is the measured C/I which is used to indicate the voice quality in the system. The higher the measured value, the better. The other is the specified C/I [$(C/I)_s$], which is a specified value for a specified cellular system. For example, the $(C/I)_s$ in the AMPS system is 18 dB. Since in analog and TDMA systems, because of spectral and geographical separations, the interference I is much lower than the received signal C, sometimes we can utilize field strength meters to measure C to determine the coverage of each cell. The field strength meter therefore becomes a useful tool in designing the TDMA system. In CDMA all the traffic channels are served solely by a single radio channel in every cell.[1-4] Therefore, in an m-voice channel cell, one of the m traffic channels is the desired channel and the remaining $m - 1$ traffic channels are the interference channels. In this case, the interference is much stronger than the desired channel. Then C/I is hard to obtain by using a signal strength meter. Thus, the key elements in designing a CDMA system are different from those in designing a TDMA system.

Relationship between C/I and FER. In CDMA, the key element is E_b/I_o (energy per bit/power per hertz), which is related to the frame error rate. An acceptable speech quality of a specified vocoder would determine the FER which is related to E_b/I_o at a given vehicle speed. From a system design aspect, we consider the system performance with all the vehicle speeds and environmental conditions and come up with a specified E_b/I_o. Now we can design the CDMA system on the basis of the specified E_b/I_o. The following equation is used:

$$\frac{C}{I} = \left(\frac{E_b}{I_o}\right)\left(\frac{R_b}{B}\right)\eta \tag{16.4-1}$$

where R_b is the bits per second, B is the CDMA channel bandwidth, and η is the speech activity cycle in percent. From Eq. (16.4-1), B/R_b is the processing gain (PG), which is known in a given CDMA system. E_b/I_o and η are also known in the system. Then the C/I of each CDMA channel can be obtained. Each coded chanel in CDMA can be treated as a frequency channel in FDMA or TDMA. If the coded channels are sent over a cable transmission medium, the interference among the coded channels can be treated as adjacent channel interference. Due to the nature of channel orthogonality, the interference should be very small. But in the mobile radio environment, because of the multipath wave phenomenon, the orthogonality among the channels cannot be held. Therefore, the processing gain is the only interference protection among the channels.

E_b/I_o always varies in order to meet a specified FER under different conditions. From Eq. (16.4-1) we can find a required $(C/I)_s$ from a specified $(E_b/I_o)_s$ in a worst-case scenario for designing the system. However, the values of $(E_b/I_o)_s$ for the forward link channels and for the reverse-link channels are different because of their different modulation schemes. Therefore, we may have two different requirements for C/I: a $(C/I)_F$ for the forward link channels and a $(C/I)_R$ for the revese link channels.

16.4.3 Uniform cell scenario

Now we try to find the design parameters of each cell for the forward link and the reverse link in a realistic uniform capacity condition.

For the forward link. A worst-case scenario is used to find the relation among the transmitted powers of all cell sites. First we form an equation which relates the C/I received at a mobile location A (Fig. 16.25) to the transmitted powers of all cell sites:

$$C/I = \frac{\alpha_1 \cdot R^{-4}}{\underbrace{\alpha(m_1 - 1)R^{-4}}_{\text{self cell}} + \underbrace{(\alpha_2 m_2 + \alpha_3 m_3)R^{-4}}_{\text{2 adjacent cells}} + \underbrace{\beta(2R)^{-4}}_{\text{3 intermediate cells}} + \underbrace{\gamma(2.633R)^{-4}}_{\text{6 distant cells}}} \tag{16.4-2}$$

where α_i (i = 1, 3) is the transmitted power of each voice channel in the cell and m_i is the number of channels per cell. β and γ are the transmitted powers of the combined adjacent cells at a distance $2R$

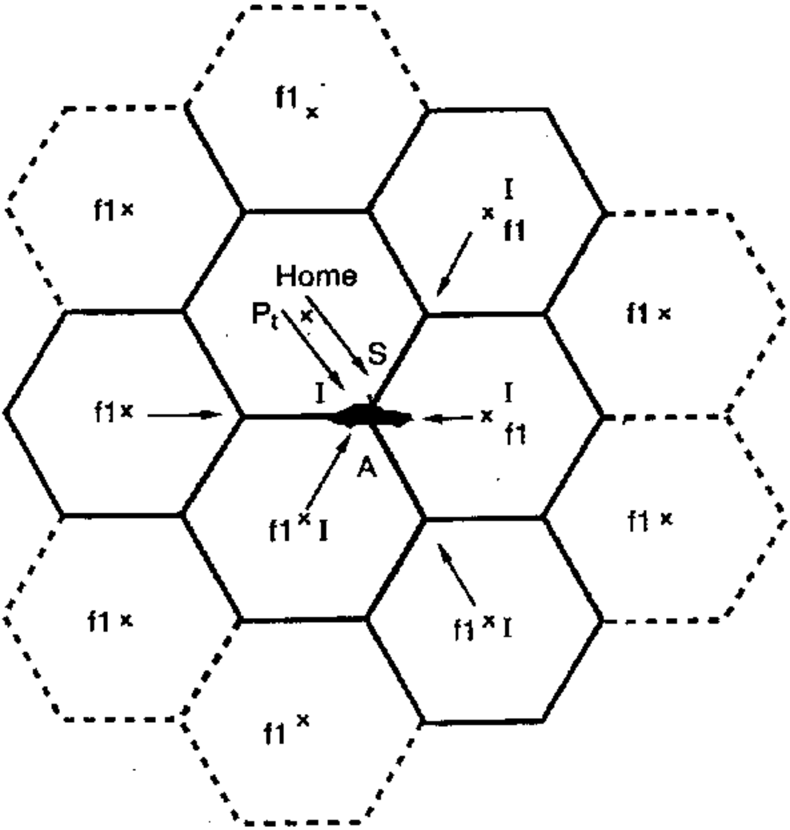


Figure 16.25 CDMA system and its interference (from a forward link scenario).

and 2.633R, respectively. By solving Eq. (16.4-2) we can determine m_i as follows:

$$m_1 = \left(\frac{1}{C/I} + 1\right) - \left[\frac{\alpha_2 m_2 + \alpha_3 m_3}{\alpha_1}\right] - \frac{\beta}{\alpha_1}(2)^{-4} - \frac{\gamma}{\alpha_1}(2.633)^{-4} \tag{16.4-3}$$

Case A. No adjacent cell interference. Let $\alpha_2 = \alpha_3 = \beta = \gamma = 0$ in Eq. (16.4-3). Then

$$m_1 = \frac{1}{(C/I)} + 1 \tag{16.4-4}$$

If the value of C/I obtained from Eq. (16.4-1) is $C/I = -17$ dB, then $m_1 = 51$, the maximum voice channels in a cell.

Case B. No interference other than from the two close-in interfering cells. In Eq. (16.4-3), the third and fourth terms are much smaller in value than the first two terms and therefore can be neglected. Then

$$\alpha_1 = \frac{\alpha_2 m_2 + \alpha_3 m_3}{\frac{1}{C/I} + 1 - m_1} \tag{16.4-5}$$

If $C/I = -17$ dB, and the assigned voice channels at three cells are $m_1 = 30$, $m_2 = 25$, and $m_3 = 15$, respectively, then Eq. (16.4-5) becomes:

$$\alpha_1 = \frac{25\alpha_2 + 15\alpha_3}{51 - 30} = 1.19\alpha_2 + 0.714\alpha_3 \tag{16.4-6}$$

Equation (16.4-6) expresses the relationship among α_1, α_2, and α_3.

The total transmitted power P in each cell site is $P_1 = \alpha_1 m_1$, $P_2 = \alpha_2 m_2$, $P_3 = \alpha_3 m_3$. Thus P_1, P_2 and P_3 are the maximum transmitted powers of the three cells. Then Eq. (16.4-5) can be simplified to:

$$\left(\frac{1}{C/I} + 1\right)\frac{P_1}{m_1} = P_1 + P_2 + P_3 \tag{16.4-7}$$

Following the same derivation steps, we can obtain the following equations:

$$\left(\frac{1}{C/I} + 1\right)\frac{P_2}{m_2} = P_1 + P_2 + P_3 \tag{16.4-8}$$

$$\left(\frac{1}{C/I} + 1\right)\frac{P_3}{m_3} = P_1 + P_2 + P_3 \tag{16.4-9}$$

The relationship of the three maximum transmitted powers of the three cells is:

$$\frac{P_1}{m_1} = \frac{P_2}{m_2} = \frac{P_3}{m_3} \tag{16.4-10}$$

Deduced from Eq. (16.4-10), a design criterion which we will use in general for a CDMA system of N cells is

$$\frac{P_i}{m_i} = \frac{P_j}{m_j} = \text{constant} \tag{16.4-11}$$

where i indicates the i cell and j indicates the j cell. Eq. (16.4-11) indicates that the more voice channels generated, the more transmit power is needed. Therefore, either applying power control to the voice channels in a cell such that more voice channels can be provided with a given transmit power, or using fewer channels in a cell such that the transmit power P will decrease, will reduce interference.

For the reverse link. The worst-case scenario (shown in Fig. 16.26) is also used in the reverse link analysis. Assume that all the mobile units traveling in the two adjacent cells will be located at the cell boundary of the home cell. From the reverse link, the powers of the m_1 voice

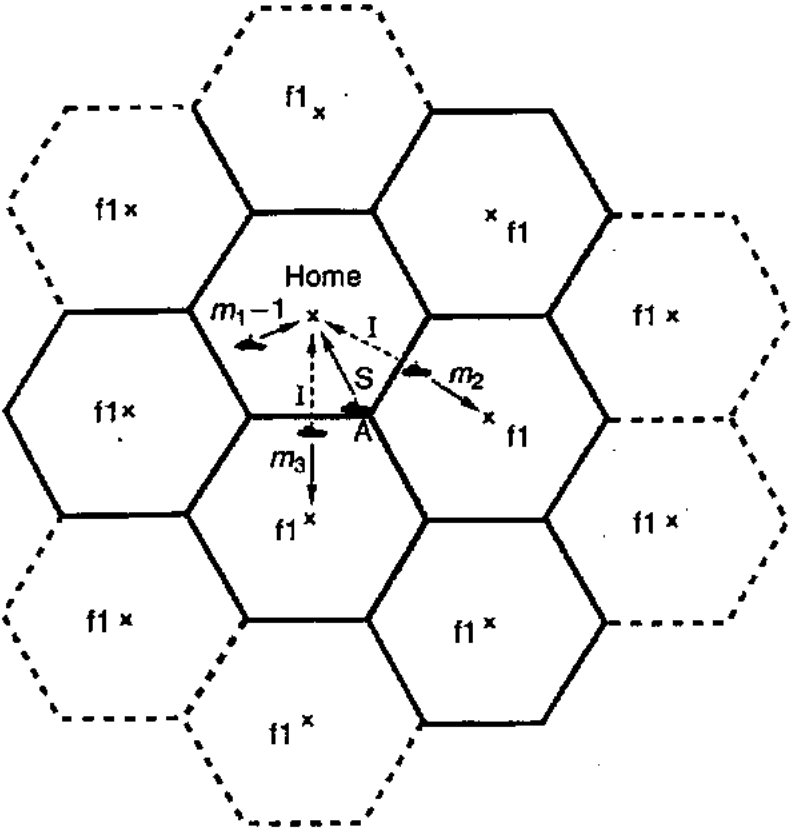


Figure 16.26 CDMA system and its interference (from a reverse link scenario).

signals received at the home site are the same, because of the power control implementation to overcome the near-to-far interference.

Let the received signal from a desired mobile unit at the home cell site be C. Assume that each signal of other m_1 channels received at the home site in Fig. 16.26 is also C. Also, assume that the interference of certain mobile units, say rm_1, from the two adjacent cells comes from the cell boundary. Because of the power control in each adjacent cell, the interference coming from the adjacent cell for each voice channel would roughly be C as received by the home cell site. The received C/I at the desired voice channel can be expressed as:

$$C/I = \frac{C}{(m_1 - 1) \cdot C + r_{12} \cdot m_2 C + r_{13} \cdot m_3 C} \tag{16.4-12}$$

$$= \frac{1}{m_1 - 1 + r_{12} m_2 + r_{13} \mathrm{m}_3}$$

where r_{12} and r_{13} are a portion of the total number of voice channels in adjacent cells that will interfere with the desired signal at the home cell, which is cell 1.

From Eq. (16.4-12), the worst-case scenario is when:

$$m_1 + r_{12} m_2 + r_{13} m_3 \leq \frac{1}{C/I} + 1 \tag{16.4-13}$$

Following the same steps, we find:

$$r_{21} m_1 + m_2 + r_{23} m_3 \leq \frac{1}{C/I} + 1 \tag{16.4-14}$$

$$r_{31} m_1 + r_{32} m_2 + m_3 \leq \frac{1}{C/I} + 1 \qquad ((16.4\text{-}15)$$

The value of r depends on the size of the overlapped region in the adjacent cell, and can be reasonably assumed as 1/6 (which is 0.166) if the system is properly designed.

If $C/I = -17$ dB, which is 50, and $r_{12} = r_{13} = 0.166$, then Eq. (16.4-13) becomes:

$$m_1 + 0.166(m_2 + m_3) = 51 \tag{16.4-13a}$$

The relationships among the numbers of voice channels in each cell, m_1, m_2, and m_3, are expressed in Eqs. (16.4-13), (16.4-14), and (16.4-15).

Designing a CDMA system. From the reverse-link scenario, we can check to see whether all the conditions expressed in Eqs. (16.4-13), (16.4-14), and (16.4-15) can be met. The main elements in these equations are the demanded voice channels, m_1, m_2, and m_3. For representative values of these terms, we can determine the maximum transmitted power of each cell from the forward link equations, Eqs. (16.4-7) to (16.4-10).

Example 16.1. Given $C/I = 17$ dB and all the r's, $r = r_{ij} = 0.3$:

Case 1: Let the demanded voice channels be $m_1 = 30$, $m_2 = 25$, $m_3 = 15$. Checking the conditions in Eqs. (16.4-13), (16.4-14), and (16.4-15), we find:

$$30 + 0.3\,(25 + 15) = 42 < 51 \qquad \text{(OK)}$$

$$25 + 0.3\,(30 + 15) = 38.5 < 51 \qquad \text{(OK)}$$

$$15 + 0.3\,(30 + 25) = 31.5 < 51 \qquad \text{(OK)}$$

Since the cell sizes of the three cells are the same,

$$\alpha_1 = \alpha_2 = \alpha_3 = CR^{-4}$$

Assume $\alpha_1 = \alpha_2 = \alpha_3 = 100$ mW. Then

$$P_1 = 30 \times 0.1 = 3\text{ W}$$

$$P_2 = 25 \times 0.1 = 2.5\text{ W}$$

$$P_3 = 15 \times 0.1 = 1.5\text{ W}$$

Case 2: Let the demanded voice channels be $m_1 = 40$, $m_2 = 30$, $m_3 = 20$. Checking the conditions in Eqs. (16.4-13), (16.4-14), and (16.4-15), we find:

$$40 + 0.3\,(30 + 20) = 55 > 51 \qquad \text{(does not meet the condition)}$$

$$30 + 0.3\,(40 + 20) = 48 < 51 \qquad \text{(OK)}$$

$$20 + 0.3\,(40 + 30) = 41 < 51 \qquad \text{(OK)}$$

The number of demanded voice channels should be reduced before the system is designed.

16.4.4 Nonuniform cell scenario

Transmit power on the forward link channels. We may first assign the number of voice channels m in each cell according to demographic data. Then we may calculate the total transmit power on the forward link channels in each cell from a worst-case scenario as shown in Fig. 16.27.

All the cell sizes are not the same in a nonuniform CDMA system. We consider only the three cells most affected by the locations of the three vehicles. The vehicles are at the most interference-prone location in each cell.

In this case, the $(C/I)_F$ received at vehicle 1 is

$$(C_1/I_1)_F = \frac{\alpha_1 R_1^{-4}}{(m_1 - 1)\alpha_1 R_1^{-4} + \alpha_2 m_2 R_2^{-4} + \alpha_3 m_3 R_3^{-4} + I_{a_1}} \qquad (16.4\text{-}12)$$

where I_{a1} is the interference coming from other cells outside the three. I_{a1} is usually very small compared to the second and third terms in the denominator and can be neglected.

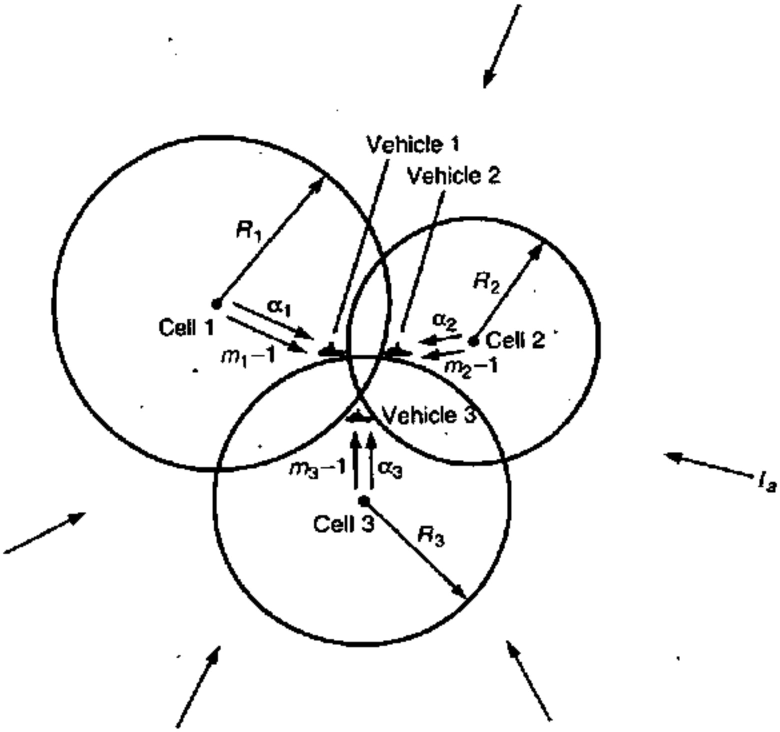


Figure 16.27 The worst-case scenario for forward link channel reception in a nonuniform CDMA system.

The received $(C/I)_F$ at vehicle 2 is

$$(C_2/I_2)_F = \frac{\alpha_2 R_2^{-4}}{(m_2 - 1)\alpha_2 R_2^{-4} + \alpha_1 m_1 R_1^{-4} + \alpha_3 m_3 R_3^{-4} + I_{\alpha 2}} \qquad (16.4\text{-}17)$$

The received $(C/I)_F$ at vehicle 3 is

$$(C_3/I_3)_F = \frac{\alpha_2 R_2^{-4}}{(m_3 - 1)\alpha_3 R_3^{-4} + \alpha_1 m_1 R_1^{-4} + \alpha_2 m_2 R_2^{-4} + I_{\alpha 3}} \qquad (16.4\text{-}18)$$

Let

$$(C_1/I_1)_F = (C_2/I_2)_F = (C_3/I_3)_F = (C/I)_F$$

and

$$I_{\alpha 1} = I_{\alpha 2} = I_{\alpha 3} = 0$$

Simplifying Eqs. (16.4-16, 16.4-17 and 16.4-18), we obtain respectively:

$$\alpha_1 m_1 + \alpha_2 m_2 \left(\frac{R_2}{R_1}\right)^{-4} + \alpha_3 m_3 \left(\frac{R_3}{R_1}\right)^{-4} = \alpha_1 \left[\frac{1}{(C/I)_F} + 1\right] = \alpha_1 G \quad (16.4\text{-}19)$$

$$\alpha_1 m_1 \left(\frac{R_1}{R_2}\right)^{-4} + \alpha_2 m_2 + \alpha_3 m_3 \left(\frac{R_3}{R_2}\right)^{-4} = \alpha_2 G \quad (16.4\text{-}20)$$

$$\alpha_1 m_1 \left(\frac{R_1}{R_3}\right)^{-4} + \alpha_2 m_2 \left(\frac{R_2}{R_3}\right)^{-4} + \alpha_3 m_3 = \alpha_3 G \quad (16.4\text{-}21)$$

Solving Eqs. (16.4-19), (16.4-20) and (16.4-21) we come up with the following relation:

$$\alpha_1 R_1^{-4} = \alpha_2 R_2^{-4} = \alpha_3 R_3^{-4} \quad (16.4\text{-}22)$$

Also, assume that the minimum values of α_1, α_2, and α_3 will be α_1^0, α_2^0, and α_3^0, respectively, which are based purely on the received level of individual voice channels at the vehicle locations:

$$\begin{aligned} \alpha_1 &\geq \alpha_1^0 = C_0 R_1^{+4} + k \\ \alpha_2 &\geq \alpha_2^0 = C_0 R_2^{+4} + k \\ \alpha_3 &\geq \alpha_3^0 = C_0 R_3^{+4} + k \end{aligned} \quad (16.4\text{-}23)$$

where C_0 is the required signal level received at the vehicle location and k is a constant related to the antenna heights at the cell sites.

Now the total transmit power of each cell site will be

$$\begin{aligned} P_1 &= m_1 \alpha_1 \\ P_2 &= m_2 \alpha_2 \\ P_3 &= m_3 \alpha_3 \end{aligned} \quad (16.4\text{-}24)$$

Transmit power on the reverse link channels. On the reverse link channels, we use the same worst-case scenario (Fig. 16.28). According to the power control algorithm, all the signals will be the same when they reach the cell site. The vehicle 1 signal received at cell site 1 is C_1, the rest of the signals are considered interference.

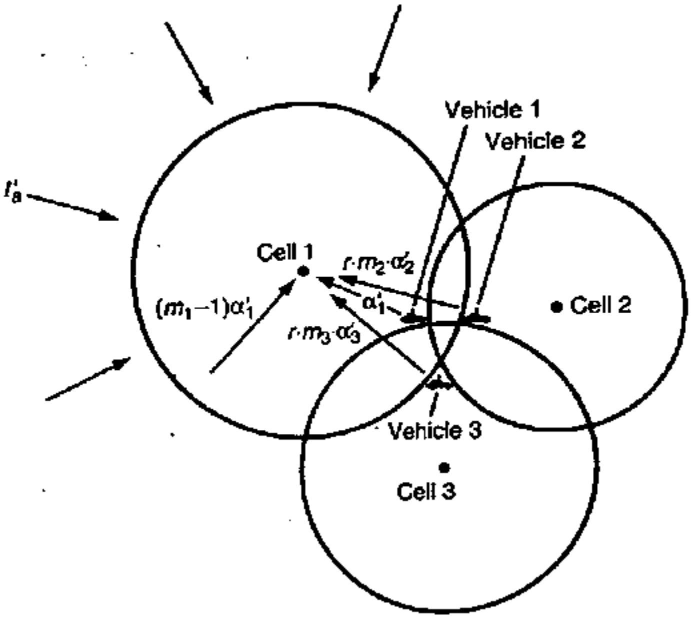


Figure 16.28 The worst-case scenario for reverse-link channel reception in a nonuniform CDMA system.

$$(C_1/I_1)_R \geq \frac{\alpha'_1 R_1^{-4}}{(m_1 - 1)\alpha'_1 R_1^{-4} + r_{12} m_2 \alpha'_2 R_1^{-4} + r_{13} m_3 \alpha'_3 R_1^{-4} + I'_{a1}} \tag{16.4-25}$$

where α'_1, α'_2, and α'_3 are the powers of individual channels transmitted back to their corresponding cell sites, r_{12} and r_{13} are the portion of the total number of voice channels in adjacent cells that will interfere with the desired signal at cell 1, and I'_{a1} is the interference coming from vehicles in cells other than cell 2 and cell 3. I'_{a1} is a relatively small value and can be neglected.

Utilizing the same steps, we can derive the following two equations for the two other cases.

Cell site 2 receives the vehicle 2 signal:

$$(C_2/I_2)_R \geq \frac{\alpha'_2 R_2^{-4}}{r_{21} m_1 \alpha'_1 R_2^{-4} + (m_2 - 1)\alpha'_2 R_2^{-4} + r_{23} m_3 \alpha'_3 R_2^{-4}} \tag{16.4-26}$$

Cell site 3 receives the vehicle 3 signal:

$$(C_3/I_3)_R \geq \frac{\alpha_3'R_3^{-4}}{r_{31}m_1\alpha_1'R_3^{-4} + r_{32}m_2\alpha_2'R_3^{-4} + (m_3 - 1)\alpha_3'R_3^{-4}} \quad (16.4\text{-}27)$$

where r is the percentage of total channels from the interfering cell that would be received by the, cell site. Simplifying Eqs. (16.4-25), (16.4-26), and (16.4-27) we obtain:

$$(I/C)_R \geq (m_1 - 1) + r_{12}m_2\frac{\alpha_2'}{\alpha_1'} + r_{13}m_3\frac{\alpha_3'}{\alpha_1'} \quad (16.4\text{-}28)$$

$$(I/C)_R \geq r_{21}m_1\frac{\alpha_1'}{\alpha_2'} + (m_2 - 1) + r_{23}m_3\frac{\alpha_3'}{\alpha_1'} \quad (16.4\text{-}29)$$

$$(I/C)_R \geq r_{31}m_1\frac{\alpha_1'}{\alpha_3'} + r_{32}m_2\frac{\alpha_2'}{\alpha_3'} + (m_3 - 1) \quad (16.4\text{-}30)$$

where

$$(C/I)_R = (C_1/I_1)_R = (C_2/I_2)_R = (C_3/I_3)_R$$

All the coefficients in Eq. (16.4-28) to Eq. (16.4-30) involve the transmit power of a voice channel in each of the three cells, α_1', α_2' and α_3'.

For the same reason stated in the derivation of Eq. (16.4-23), the minimum values of α_1', α_2', and α_3' can be defined as follows:

$$\begin{aligned} \alpha_1' &\geq \alpha_1^0 = C_0R_1^4 + k \\ \alpha_2' &\geq \alpha_2^0 = C_0R_2^4 + k \\ \alpha_3' &\geq \alpha_3^0 = C_0R_3^4 + k \end{aligned} \quad (16.4\text{-}31)$$

where R_1, R_2, and R_3 are the radii of the three cells and k is a constant related to the antenna heights as the cell sites. We may replace all the α' terms in Eqs. (16.4-28), (16.4-29), and (16.4-30) with the equivalent α^0 terms in Eq. (16.4-31). Equations (16.4-28), (16.4-29) and (16.4-30) become

$$(I/C)_R \geq (m_1 - 1) + r_{12}m_2\left(\frac{R_2}{R_1}\right)^4 + r_{13}m_3\left(\frac{R_3}{R_1}\right)^4 \quad (16.4\text{-}32)$$

$$(I/C)_R \geq r_{21}m_1\left(\frac{R_1}{R_2}\right)^4 + (m_2 - 1) + r_{23}m_3\left(\frac{R_3}{R_2}\right)^4 \quad (16.4\text{-}33)$$

$$(I/C)_R \geq r_{31}m_1\left(\frac{R_1}{R_3}\right)^4 + r_{32}m_2\left(\frac{R_2}{R_3}\right)^4 + m_3 - 1 \quad (16.4\text{-}34)$$

Under the physical condition, the following relationships have to be held. The values m_1, m_2, and m_3 have to be

$$m_1, m_2, m_3 < \frac{1}{(C/I)_R} + 1 \tag{16.4-35}$$

which has been derived in Eq. (16.3-4).

Designing a CDMA system. We first have to check whether all the requirements expressed in Eqs. (16.4-32) to (16.4-32) are met with our given conditions. If they are met, then we can find the transmit powers P_1, P_2, and P_3 from Eq. (16.4-24). Usually, among the three equations, only one dominates. If that one meets the given conditions, the other two will meet them also. The following example addresses this point.

Example 16.2. Given: $R_1 = 4$ km, $R_2 = 6$ km, $R_3 = 5$ km, and $(C/I)_R = -17$ dB. Also assume that:

$$r_{13} = r_{31} = 0.3$$

$$r_{21} = r_{12} = 0.2$$

$$r_{23} = r_{32} = 0.25$$

Then checking the conditions in Eqs. (16.4-32) through (16.4-34) we obtain:

$$50 \geq m_1 - 1 + 1.0125m_2 + 0.7324m_3 \tag{16.4-36}$$

$$50 \geq 0.0395m_1 + m_2 - 1 + 0.1205m_3 \tag{16.4-37}$$

$$50 \geq 0.1229m_1 + 0.5184m_2 + m_3 - 1 \tag{16.4-38}$$

Among the three equations, Eq. (16.4-36) should be checked first.

Let $m_1 = 20$. Then

$$31 \geq 1.0125m_2 + 0.7324m_3 \tag{16.4-39}$$

$$50.21 \geq m_2 + 0.1205m_3 \tag{16.4-40}$$

$$48.54 \geq 0.5184m_2 + m_3 \tag{16.4-41}$$

Among the three equations, the condition of Eq. (16.4-39) is the limiting condition. Also, we may find the conditions for $m_1 = 15$ and $m_1 = 25$ as follows:

$$36 \geq 1.0125m_2 + 0.7324m_3 \qquad (m_1 = 15) \tag{16.4-42}$$

$$26 \geq 1.0125m_2 + 0.7324m_3 \qquad (m_1 = 25) \tag{16.4-43}$$

The three curves, $m_1 = 15, 20, 25$, are plotted in Fig. 16.29 for various values of m_2 and m_3. From the figure, we may pick three values such as $m_1 = 25$, m_2

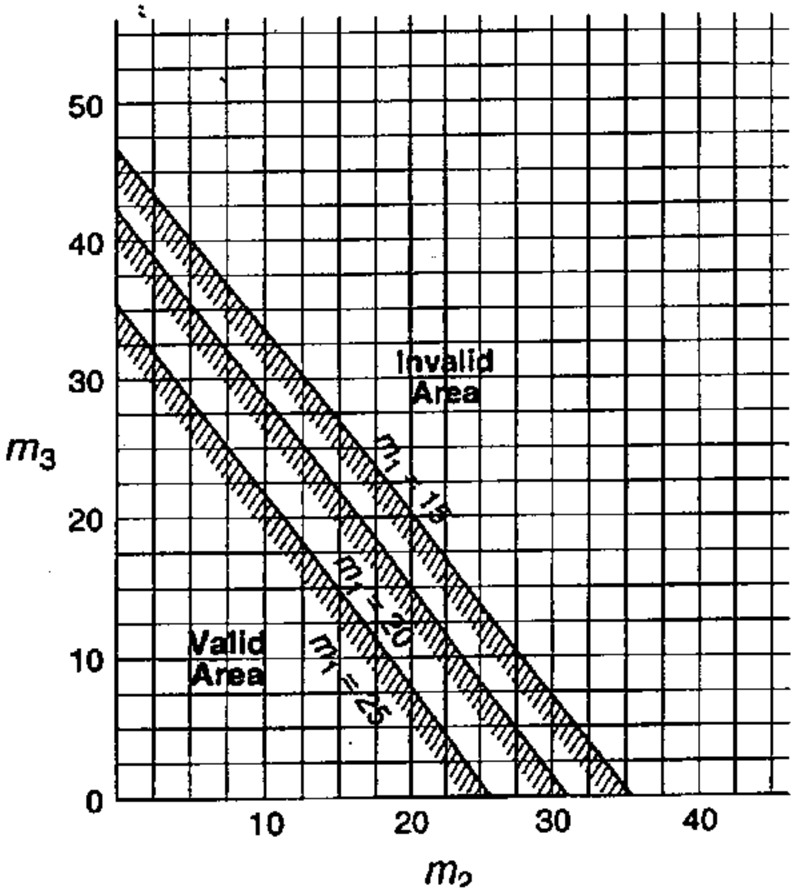


Figure 16.29

= 20, and $m_3 = 7$, and assume that $C = -95$ dBm. Then the transmit power of each voice channel in the respective cell is:

$$\alpha_1 = -95 \text{ dBm} + 40 \log R_1^4 + k \qquad \text{(for cell 1)}$$

$$\alpha_2 = -95 \text{ dBm} + 40 \log R_2^4 + k \qquad \text{(for cell 2)}$$

$$\alpha_3 = -95 \text{ dBm} + 40 \log R_3^4 + k \qquad \text{(for cell 3)}$$

where k is a constant depending on the antenna height.

From Eq. (16.4-31) the total power will be:

$$P_1 = m_1 a_1$$

$$P_2 = m_2 a_2$$

$$P_3 = m_3 a_3$$

References

1. W. C. Y. Lee, *Mobile Cellular Telecommunications Systems,* McGraw Hill, 1989, p. 379.
2. V. H. MacDonald, "The Cellular Concept," *Bell System Technical Journal,* vol. 58, January 1979, pp. 15–42.
3. W. C. Y. Lee, "Spectrum Efficiency in Cellular," *IEEE Transactions of Vehicular Technology,* May 1989, pp. 69–75.
4. W. C. Y. Lee, "Smaller Cell for Greater Performance," *IEEE Communication Magazine,* November 1991, pp. 19–23.
5. M. Cooper and R. Roy, "SDMA Technology—Overview and Development Status," ArrayComm-ID-010, ArrayComm, Inc., Mountain View, Calif.
6. W. C. Y. Lee, "Lee's Model," *IEEE VTS Conference Record 1992,* Denver, May 11, 1992, pp. 343–348.
7. W. C. Y. Lee, *Mobile Communications Engineering,* McGraw Hill, 1982, p. 202.
8. K. Gilhousen, I. Jacobs, R. Padovani, A. Viterbi, L. Weaver, C. Wheatley, "On the Capacity of a Cellular CDMA System," *IEEE Transactions on Vehicular Technology,* Vol. 40, May 1991, pp. 303–312.
9. R. Pickholtz, L. Milstein, D. Schilling, "Spread Spectrum for Mobile Communications," *IEEE Transactions on Vehicular Technology,* Vol. 40, May 1991, pp. 313–322.
10. W. C. Y. Lee, "Overview of Cellular CDMA," *IEEE Transactions on Vehicular Technology,* Vol. 40, May 1991, pp. 291–302.
11. ETSI/TC, "Recommendation GSM 01.02," ETSI/PT12, January 1990.
12. F. Anderson, W. Christensen, L. Fullerton, B. Kortegaard, "Ultra-Wideband Beamforming in Sparse Arrays," *IEEE Proceedings,* vol. 138, no. 4, August 1991, pp. 342–346.
13. R. A. Scholtz, "Multiple Access with Time-Hopping Impulse Modulation," MILCOM 1993, Boston, October 11–14, 1993.
14. R. A. Comroe and D. J. Costello, Jr., "ARQ Schemes for Data Transmission in Mobile Radio Systems," *IEEE Transactions on Vehicular Technology,* vol. VT-33, August 1984, pp. 88–97.
15. K. Raith and J. Uddenfeldt, "Capacity of Digital Cellular TDMA Systems," *IEEE Trans. on Vehicular Technology,* vol. 40, May 1991, pp. 323–332. W. C. Y. Lee, "In-building Telephone Communication System," U.S. patent office number 5,349,631, Sept. 20, 1994.
16. J. C. Liberti, Jr., and T. S. Rappaport, "Analytical Results for Capacity Improvement in CDMA," *IEEE Trans on VT,* vol. 43, August 1994, pp. 680–690.
17. W. C. Y. Lee, "An Innovative Microcell System," *Cellular Business,* December 1991, pp. 42–44.
18. W. C. Y. Lee, "Applying the Intelligent Cell Concept to PCS," *IEEE Trans. on VT,* vol. 43, August 1994, pp. 672–679.
19. Allen Telecomm Co. and 3dBM Co. manufacture analog converters, ADC Kentron manufacture digital converters.
20. D. Parsons, *The Mobile Radio Propagation Channel,* Pentech Press, London, 1992.
21. H. H. Xia, H. L. Bertoni, L. R. Maciel, A. Lindsay-Stewart, and R. Low, "Microcellular Propagation Characteristics for Personal Communications in Urban and Sub-

urban Environments," *IEEE Transactions on Vehicular Technology,* Part II Special Issue on Future PCS Technologies, vol. 43, August 1994.
22. W. C. Y. Lee, Mobile Communications Design Fundamentals, John Wiley & Sons, 1993, section: microcell prediction model.
23. W. C. Y. Lee, "Key Elements in Designing a CDMA System," *IEEE VTC '94 Conference Record,* Stockholm, Sweden, June 8–10, 1994, pp. 1547–1550.

Chapter 17

Intelligent Network for Wireless Communications

17.1 Advanced Intelligent Network (AIN)[1-3]

AIN is a network evolving from the intelligent network (IN). It has an independent architecture which allows telecommunication service operators to rapidly create and modify services for both network performance and customers' needs.

In the intelligent network concept, the service providers need more control for new service offerings. The IN is able to separate the specification, creation, and control of telecommunication services from the physical switching network such that the HLR (home location register) and the VLR (visitor location register) are no longer integrated in the MTSO (mobile telephone switching office).

17.1.1 Intelligent network evaluation

In the '60s, crossbar switches were developed and demonstrated to be very reliable switches. However, crossbar switches are mechanical and do not provide the intelligence. Then the No. 1 ESS (electronic switching system) was developed by AT&T and provided stored program control (SPC) capability. In 1965, SPC delivered call waiting and centrex features on No. 1 ESS. In the '70s, ESSs provided intelligent in-network management and maintenance, and offered operations systems (OS), and operation, administration, and maintenance (OA&M). In the '80s, the intelligent network introduced centralized databases and provided the network database services such as 800 toll-free calls and calling card calls. In 1983, the centralized databases were located at the service control point (SCP) to support alternate billing services

(ABS) and 800 calling. The data flow from the physical switches to the SCP is via SS7 (Signaling System No. 7) network. There are several intelligent networks:

IN/1—Functionality is distributed not only at the switches but also at the SS7 network, SCPs and OSs.

IN/2—To expand the switching and SCP capabilities known as *functional components* (FC), and with these expansions to form a new system called the *intelligent peripheral* (IP). It is capable of supporting a wide range of voice and data services.

AIN—The IN evolution began in the '90s at a forum called Multivendor Interaction (MVI) in which 16 vendors participated. AIN was defined by a series of releases. Each release contains additional architecture attributes and capabilities of supporting services.

AIN's network characteristics. AIN is evolving from IN, and its characteristics are as follows:

- Modular—divided into functional entities
- Uniform—became standard architecture
- Service independent
- Programmable network operable by either user or carrier provider, or both
- Supplier transparent—open system architecture (OSA)
- Capable of rapid introduction of new services
- Accessible for other service providers
- Common channel signaling (CCS)—using out-of-band signaling
- Service logic—invokes AIN service logic programs (SLPs)

AIN uses CCS to deliver the call set-up signaling and the network information. In this case, the traffic channels are never tied up for signaling. For example, if the called party line is detected as busy by the signaling channel, the network would not assign a traffic channel to the calling party. Thus the efficient use of the traffic channels increases. Also the use of CCS can increase the speed of process for call process and information delivery. The CCS network uses digital channels with the SS7 protocol at a rate of 56 kbps.

AIN elements. An AIN (Fig. 17.1) consists of the following elements:

Service control point. The SCP invokes service logic programs. The common channel signaling network allows the SCP to fully inter-

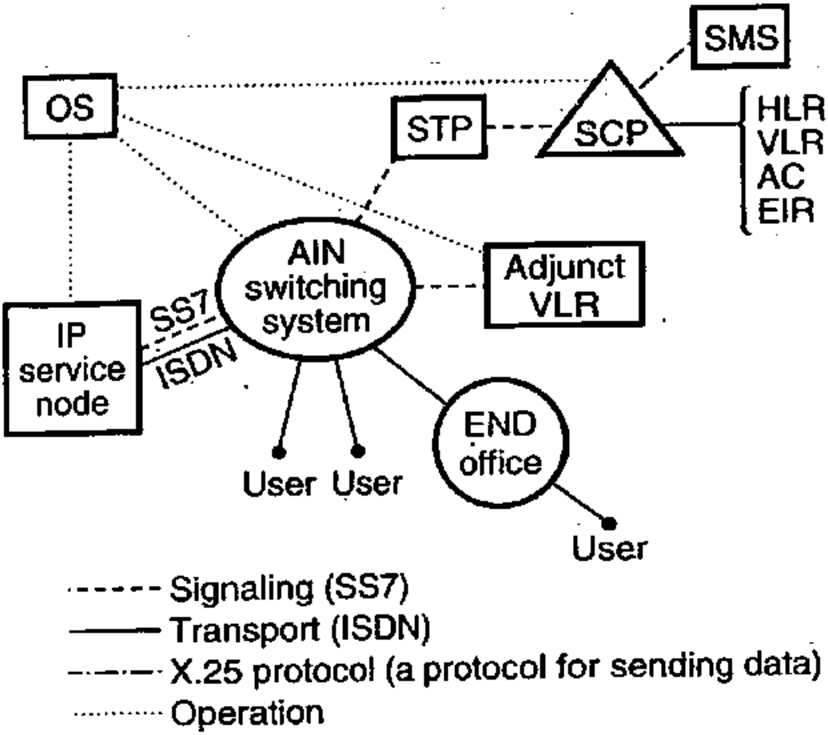


Figure 17.1 AIN system architecture.

connect with AIN switching systems through a signaling transport point (STP). The SCP supports 800 toll-free phone calls, area number calling, or personal location services.

Adjunct system. A direct link to the AIN switching system with a high-speed interface.

Service node. Communicates with AIN switch via the integrated services digital network (ISDN) access link and supports user interaction.

Intelligent peripheral. Controls and manages resources such as voice synthesis announcement, speech recognition, and digit collection.

AIN switch. Routes a call to an IP to ask for a function. When the IP completes the function, it also collects the user's information and sends it to AIN service logic (resides in SCP) via the AIN switch.

Operational system (OS). Provides memory administration, surveillance, network testing, and network traffic management maintenance and operation.

Signaling transport point (STP). The point that interconnects the SCP and AIN switching system.

Service management system (SMS). Provides three functions: (1) provision—creates service order, validation, load record; (2) maintenance—resolves record inconsistency, tests call processing logic, performs special studies; (3) administration—creates service logic, maintains service data.

Service switching point (SSP). Functions as a switch.

AIN interfaces. The interfaces between AIN network elements are

1. Between the switching system and SCPs or adjunct systems using SS7 signaling.
2. Between the switching system and IPs or service nodes using ISDN.
3. In AIN, between SCP and SMS using the X.25 protocol.
4. Between end users AIN services; may be either conventional analog or ISDN interface.

The AIN general architecture with the indicated AIN interfaces is shown in Fig. 17.1. In cellular system the channel link between the mobile switching system and the user does not use ISDN. Because a 64 kbps ISDN channel needs a bandwidth of 64 kHz for radio transmission. In cellular systems, the data rate of a channel is 16 kbps or less, and needs only a bandwidth of 25 kHz or less. Using less channel bandwidth increases more spectrum efficiency.

17.2 SS7 Network and ISDN for AIN

17.2.1 History of SS7[4]

This is an out-of-band signaling method in which a common data channel is used to convey signaling information related to a large number of trunks (voice and data). Signaling has traditionally supported (1) supervisory functions, e.g., on-hook/off-hook to indicate idle or busy status; (2) addressing function, e.g., called number; and (3) calling information, e.g., dial tone and busy signals. The introduction of electronic processors in switching systems made it possible to provide common channel signaling.

In 1976 common channel interoffice signaling (CCIS) was introduced.CCIS is based on the International Consultative Committee on Telegraphy and Telephony (CCITT) Signaling System No. 6 recommendations and called CCS6. The CCS6 protocol structure was not layered. It was a monolithic structure. The signaling efficiency was high.

In 1980 CCITT first recommended SS7, a signaling system for digital trunks. The layered approach to designing SS7 protocols was being developed for open system interconnection (OSI) data transport. Also, the HDLC (higher-level data link control) bit-oriented protocols had an influence on the development of SS7.

17.2.2 SS7 protocol model

The inefficiencies of layered protocols are far outweighed by their flexibility in realization and management of complex functions. The protocol becomes more aligned with the seven-layer OSI reference model (Fig. 17.2*a*). The seven layers are physical, data link, network, transport, session, presentation, and application. The SS7 protocol model is shown in Fig. 17.2*b* for comparison with the OSI model. In SS7, the message transfer part (MTP) provides the OSI layered protocol model as level 1 data service, level 2 link service, and level 3 network service. The full level 3 service is provided by the signaling connection control part (SCCP). SCCP provides an enhanced addressing capability that may be considered as level 3+ or a level close to level 4. Layers 4 to 6 in the OSI model do not exist in the SS7 protocol model. The transaction capabilities application part (TCAP) level and the operations maintenance and administration part (OMAP) level are considered the same as the application part (level 7) in OSI. The application service element (ASE) is at the same level as OMAP. TCAP includes protocols

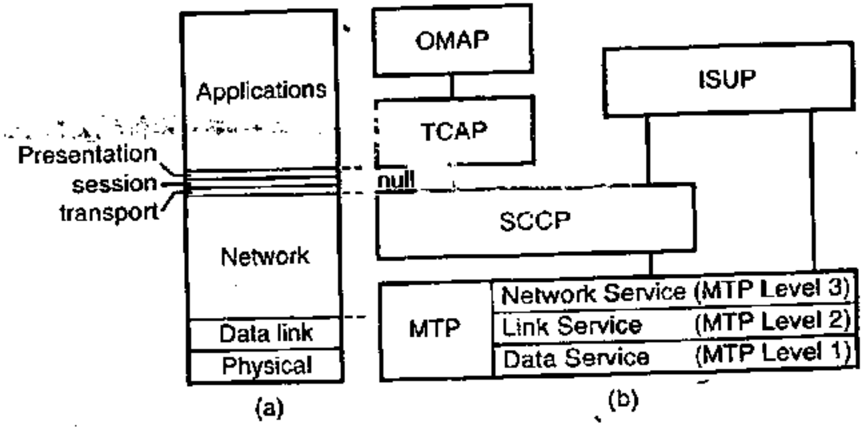


Figure 17.2. (*a*) OSI model. (*b*) SS7 protocol model.

and services to perform remote operations. The primary use of TCAP in these networks is for invoking remote procedures in supporting IN services like 800 service. OMAP provides the application protocols and procedures to monitor, coordinate, and control all the network resources which make communication based on SS7 possible. ASE is for the MTP routing verification test (MRVT), which uses the connectionless services of TCAP. MRVT is an important function of OMAP.

17.2.3 SS7 network link deployment for AIN

The SS7 links can provide high-speed service because of the common channel signaling. Based on the connection among all the resource elements, there are six links from A to F.

A link:	STP ↔ SCP STP ↔ SP/SSP
B/D and C links	STP ↔ STP
E link	STP ↔ SP/SSP
F link	SP/SSP ↔ SP/SSP

The SS7 network link deployment chart is shown in Fig. 17.3. The interfaces between any two entities are indicated by the letters from A to F.

17.2.4 ISDN[5]

Signaling has evolved with the technology of the telephone. The integrated services digital network (ISDN) is used to integrate all-digital networks in which the same digital exchanges and digital transmission paths are used for provision of all voice and data services.

Signaling in ISDN has two distinct components:

- Signaling between the user and the network node to which the user is connected (access signaling). The SS7 signaling is not used between the mobile user and network node.
- Signaling between the network nodes (network signaling)

The current set of protocol standards for ISDN signaling is Signaling System No. 7 (SS7).

ISDN-UP. In the SS7 protocol model, functions not covered by the SS7 levels will be provided by the ISDN-UP protocol, such as the signaling functions that are needed to support the basic bearer service and sup-

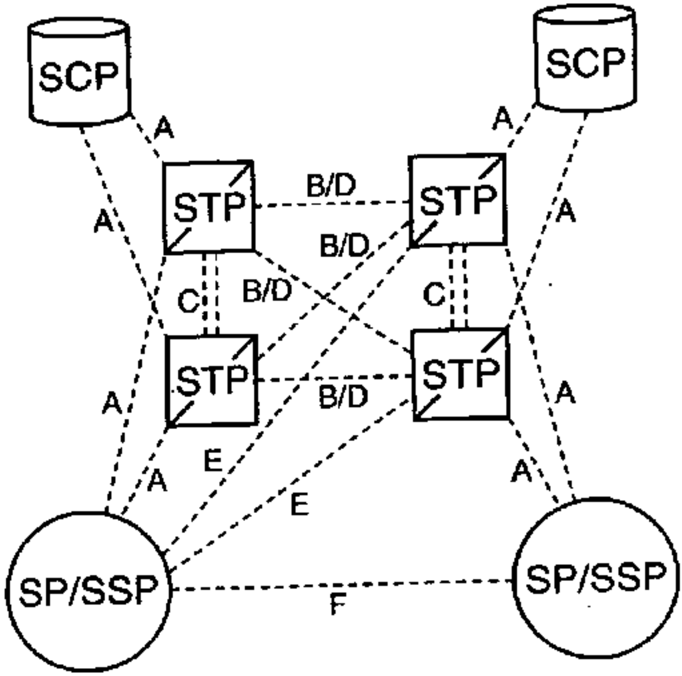


Figure 17.3 SS7 network link deployment.

plementary services for switched voice and data applications in an ISDN environment.

B-ISDN.[6] The broadband ISDN will support a range of voice, video, data, image, and multimedia services using available resources. These resources include transmission, switching and buffer capacity, and control intelligence. The target is to provide switched services over synchronous optical network/asynchronous transfer mode (SONET/ATM) transport using signaling based on the extended ISDN protocol.

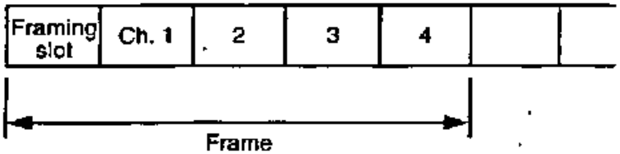
17.2.5 SONET and ATM[7,8]

A fiber-optic transport system named SONET was introduced in 1984. By 1988, as a global transmission standard, synchronous digital hierarchy (SDH) became an umbrella standard that allowed local variations. SDH is a set of interface standards which is common to all SONET equipment. The highest rate for SONET is 155-Mbps. Rates above 155 Mbps can be carried by the ATM cells. All services are divided into a series of cells and routed across the ATM network via an ATM switch which is a broad band switch. ATM is a connection-oriented packet-like switching and multiplexing principle. ATM offers flexibility and relative simplicity in network arrangements as a whole. ATM has been chosen by CCITT as the information transfer mode for B-ISDN.

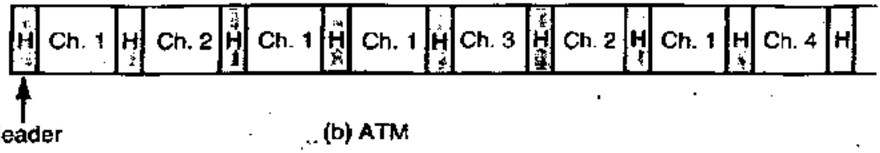
Present SONET rings use STM (synchronous transfer mode). SONET rings can be self-healing rings to provide reliable transport for high-speed switched data services such as SMDS (switched multimegabit data service) and FDDI (fiber distributed data interface interconnection). A four-channel information structure for SONET uses STM, shown in Fig. 17.4*a*. A frame consists of five time slots: a framing slot and four channel slots. Recently a SONET ring uses ATM is called SONET/ATM ring which architecture using point-to-point virtue paths overcomes the problem of inefficient and expensive use of SONET bandwidth for SMDS services. In an ATM information structure, the information is carried in fixed-size cells that consist of a header and an information field. The header contains a label that uniquely identifies a logical channel and is used for multiplexing, routing, and switching. A four-cell ATM information structure is shown in Fig. 17.4*b*. The physical transport of ATM cells is the SONET or SDH optical network.

17.3 AIN for Mobile Communication[9–12]

The AIN for mobile communication has to meet a unique requirement: the call has to reach the mobile station in a required time frame while



(a) STM



(b) ATM

Figure 17.4 The information structures of (*a*) STM and (*b*) ATM.

it is in motion. Therefore, the call processing time or the handoff time has to be within a specific limit, otherwise the mobile station can move out of the coverage area and the call either cannot be connected or will be dropped. Besides, the call has to be delivered to wherever the mobile station is; i.e., the system must have a roaming feature. The system handoff between the two different systems also needs AIN.

Two major directions in AIN for mobile communications are wireless access technology and increased network functionality. Wireless access technology is aiming at low power, light weight, efficiently used spectrum, and low-cost operation and maintenance. The increased network functionality is achieved through the use of SS7 for call control and database transactions. Mobility is the main concern in the connectionless structure of the protocol, which has to be suited to real-time application. The mobile application part (MAP) can be applied to mobile communications. The exchange of data between components of a mobile network to support end user mobility and network call control are taken care of by MAP. The MAP is an application service element. The MAP of CCITT SS7 is shown in Fig. 17.5. TCAP is composed of both the component sublayer and transaction sublayer. The component sublayer provides the exchange of protocol data units, invoking remote operations and reporting their results. The transaction sublayer is responsible for establishing a pseudo-association service for exchange of related protocol data units. The interrogations and transfer of information take place by using the ASE of the MAP and the component sublayer of TCAP. A number of MAP procedures relate to (1) location registration and cancellation, (2) handling of supplementary services, (3) retrieval of subscriber information during call establishment, (4) handoff, and (5) subscriber management including location information request and retrieval. The AIN mobile system architecture is shown in Fig. 17.6, which is the same as Fig. 17.1 except that SSP is replaced by MSC and SMS collocates with the service creation environment (SCE), which defines new features and services.

17.4 Asynchronous Transfer Mode (ATM) Technology[13–22]

ATM technology, because of its flexibility and its support of multimedia traffic, draws much interest and attention. In wire line and wireless communications, we are interested in broadband switches as mentioned in Sec. 17.2.5. The ATM switch can meet our needs. The ATM technology will be described in this section.

The interest in ATM first came from carriers and manufacturers of wide-area networking equipment, and now interest is growing in the application of ATM technology to the local and campus area network-

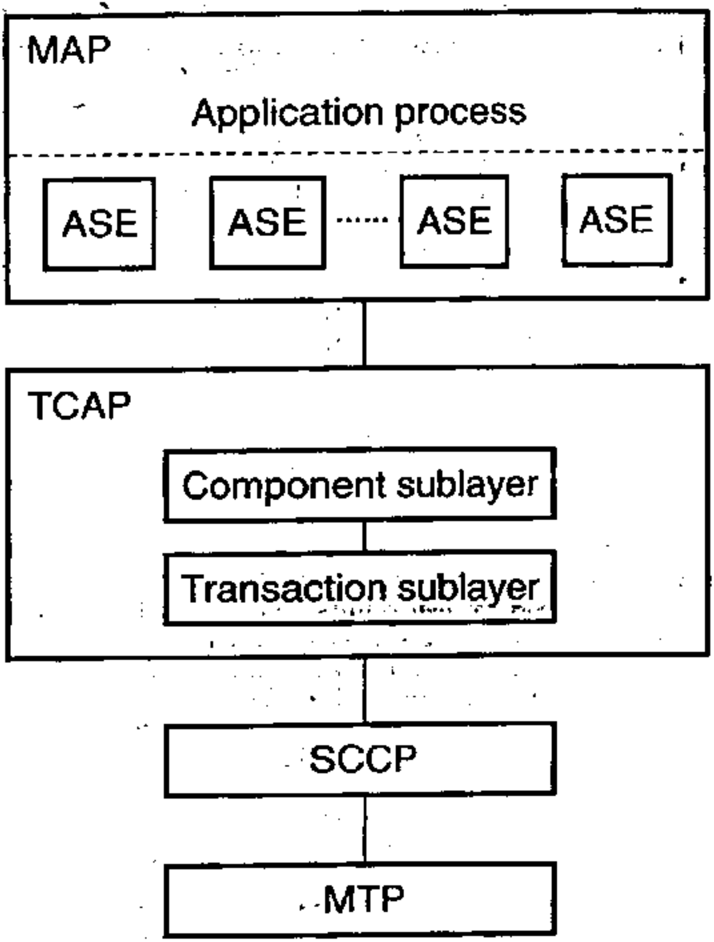


Figure 17.5 Map of CCITT SS7.

ing environment. ATM is designed to support multimedia traffic and is capable of offering seamless integration with wide-area ATM networks, both public and private. Since it offers the benefit of handling the broadband signal channels needed for the increasing volume of data communications traffic, it has been chosen for the switch of B-ISDN. The ATM network concept is shown in Fig. 17.7.

LAN applications. For bringing ATM technology to the customer premises, it must offer LAN-like service for data traffic and be compatible with the existing data communication protocols, application, and

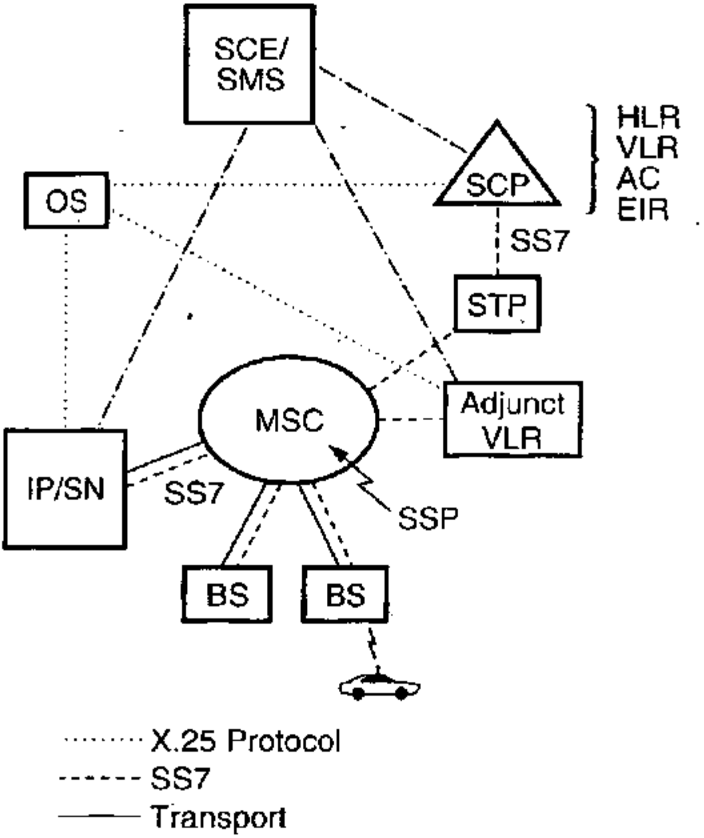


Figure 17.6 Mobile communication architecture.

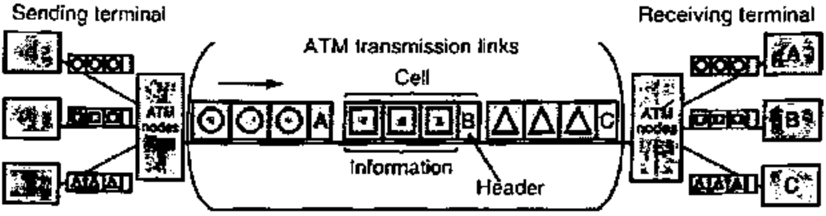


Figure 17.7 ATM network concept.

equipment. A local-area network (LAN) offers connectionless, i.e., "best effort", service for transferring variable size data packets. The term *best effort* means that the lost or corrupted packets are not retransmitted. Users are not required to establish a connection before submitting data for transmission, nor are they required to define the traffic characteristics of their data in advance of transmission.

Connectionless service. ATM switches are connection-oriented. A connectionless server (a packet switch) attached to an ATM switch can provide connectionless service. The connectionless servers are connected together with virtual paths through the ATM switches to form a "virtual overlay network," the same as is used for narrowband ISDN.

Star configuration. The physical topology of a LAN has migrated from the ring and multidrop toward the star (hub) configuration. As the bandwidth requirement of LAN approaches the gigabit per second range, switched star topologies are the most likely to be chosen in the commercial environment.

ATM packet-switching techniques. ATM is a high-speed packet-switching technique using short fixed-length packets called *cells*. Fixed-length cells simplify the design of an ATM switch at the high switching speeds involved. The short fixed-length cell reduces the delay, and most significantly the variance of delay, which is *jitter,* for delay-sensitive services such as voice and video. Therefore, short fixed cells are capable of supporting a wide range of traffic types such as voice, video, image, and various classes of data traffic.

ATM applications

1. ATM multiplexing and switching technologies are used for the B-ISDN.
2. ATM offers LAN, a high-capacity network.
3. ATM's switching technique offers seamless access to private wide-area networking.

Connection-oriented service. All ATM cells belong to a preestablished virtual connection. All traffic is segmented into cells for transmission across an ATM network. The ATM standard or broadband ISDN defines a cell as having a fixed length of 53 bytes, consisting of a header of 5 bytes and a payload of 48 bytes. Each cell's header contains a virtual channel identifier (VCI) to identify the virtual connection to which the cell belongs. An ATM switch will handle a minimum of several hundred thousand cells per second at every switch port. Each switch port will support a throughput of at least 50 Mbps, while 150 Mbps and 600 Mbps are proposed as standard ports. A switch, if it has more than 100 ports, is considered a large switch. The general structure of an ATM switch is shown in Fig. 17.8. In an ATM switch, cell arrivals are not scheduled. A number of cells from different input ports may simultaneously request the same output port. This event is called *output contention*. A single output port can transmit only one cell at a time. Thus, only one cell can be accepted for transmission and others simultaneously requesting that port must either be buffered or discarded. Therefore, the most significant aspects of the ATM switch design are (1) the topology of the switch fabric, (2) the location of the cell buffers, and (3) the contention resolution mechanism.

Switch fabric. A switch fabric can be based on time division and space division.

1. *Time division.* All cells flow across a single communication highway shared in common by all input and output ports. The communication highway may be either a shared medium such as a ring or a multidrop bus, or a shared memory as shown in Fig. 17.9. This single shared highway fixes an upper limit on the capacity for a particular implementation.
2. *Space division.* A plurality of paths is provided between the input and output ports. These paths operate concurrently so that many cells may be transmitted across the switch fabric at the same time.

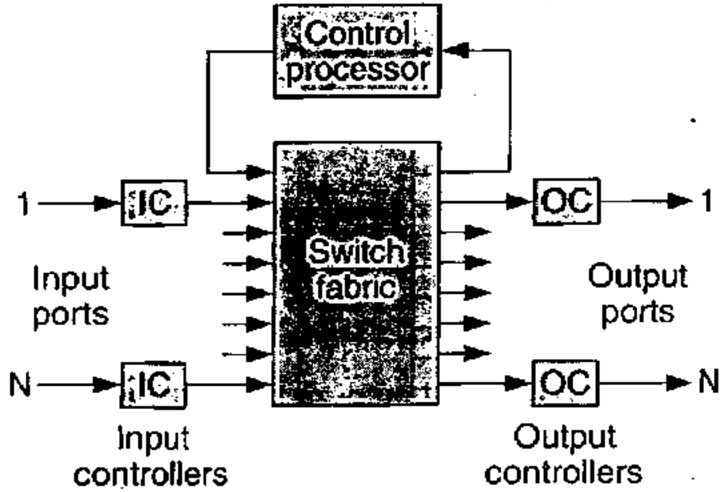


Figure 17.8 General structure of an ATM switch.

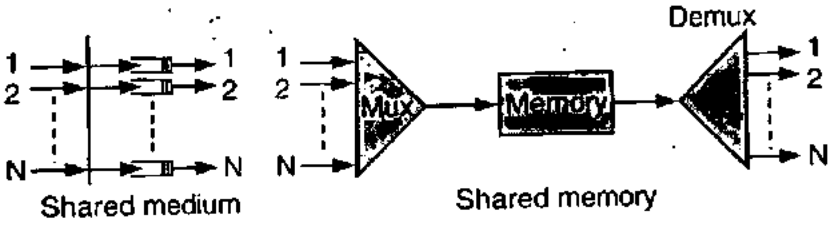


Figure 17.9 Time-division ATM switch fabrics.

Total capacity is measured as follows:

Capacity = path's bandwidth × number of paths.

The upper limit on the total capacity is theoretically unlimited. However, it is restricted by physical implementation constraints, i.e., device capability, connector restrictions, and synchronization considerations for high capacity. There are two approaches:
a. A single-path, self-routing interconnection network is most often proposed for use in ATM switch design.
b. Multiple-path networks are used to improve the performance of a single-path network or to construct large switches from switch modules. Since multiple paths are available between every input-output pair, an algorithm is required to select one of the paths.

Buffering strategies. The buffering strategy is based on whether any cell queries are located within the switch fabric (internally buffered) or outside the switch fabric (externally buffered):

1. *Internal buffering*. A single shared memory switch module may be considered internally buffered when it permits a single buffer to be shared by many input and output parts. This sharing of buffers substantially reduces the number of cell buffers required to support a given switch performance.
2. *External buffering*. Allows the cell queries to be located close to the switch ports that they serve. The absence of cell queries within the switch fabric eases the support of multiple levels of priority across the switch fabric for different classes of traffic.

Contention resolution

1. In an internally buffered switch, contention is handled by placing buffers at the point of contention.
2. In an externally buffered switch, a contention resolution mechanism is required. Three basic actions can be taken once contention is detected.

a. Backpressure. Used in the input-buffered switch design. The cell that cannot be handled at the point of contention will be sent back to the input buffers.

b. Deflection. This mechanism will route the cells in contention over a path other than the shortest path to the requested destination.

c. Loss. Pure output-buffered designs use a loss mechanism that discards cells that cannot be handled.

17.5 An Intelligent System: Future Public Land Mobile Telecommunication System (FPLMTS)[23,24]

The International Radio Consultative Committee (CCIR) has made recommendations for the third generation of land-mobile systems. The overall objectives of FPLMTS are to provide all services generally available through the fixed network (e.g., voice, fax, and data) to mobile systems. It is intended to provide these services over a wide range of user densities and geographic coverage areas. The frequency allocations were made by the World Administrative Radio Conference of 1992 (WARC '92) in the 1- to 3-GHz frequency range with an amendment of a worldwide co-primary allocation to mobile services over the frequency range 1700 to 2600 MHz. The 230 MHz of spectrum in the following bands is designated for FPLMTS:

1800 to 2025 MHz (140 MHz)
2110 to 2200 MHz (90 MHz)

In addition, the following bands are designated for mobile satellite systems:

1980 to 2010 MHz
2170 to 2200 MHz

Future enhancement

The *land* in FPLMTS refers to the land base station, which can be either a terrestrial or satellite station. Calls within the mobile system are routed to and from the intelligent network, either fixed or mobile via terrestrial or satellite links using at least four kinds of radio interface (R_1, R_2, R_3, R_4). The R_1 interface is used by mobile stations. The R_2 interface is used by indoor and outdoor personal stations (handsets). The R_3 interface is used by mobile stations communicating through a satellite, and the R_4 interface is used by pagers. All mobile calls can be connected either directly to PSTN (public service telephone network) or via a mobile switch. The mobile systems can be either a narrowband or wideband.

The requirement of developing an FPLMT system has been described. Intelligent mobile units, intelligent cells, and the intelligent network will make this intelligent system a reality.

17.6 Wireless Information Superhighway

In 1993, the United States government asked the communications and computer industry to move ahead on building the information superhighway. The information superhighway will provide the ability for many users to frequently send and receive large volumes of information.

There are two types of information superhighways: wireline and wireless. The wireline information superhighway uses optical fiber. The spectral bandwidth of optical fiber is very broad. There is apparently no limitation on assigning a number of broadband channels to the users in the wireline information superhighway system. Therefore, in developing a wireline information superhighway system, the problem is relatively simple. The most difficult task is how the information will get on and off the information superhighway because of the high volume of call traffic. A future advanced intelligent network will be developed for the information superhighway systems.

However, in developing a wireless information superhighway system, the problem is more difficult. Besides the problem of developing the wireline information superhighway, the major difficulty is how to reach and serve customers over radio waves. In the mobile radio environment there is excessive pathloss, multipath fading and dispersive time delay spread as stated in Sec. 1.6. Also, video data transmission over the information superhighway requires a large bandwidth (5 MHz or higher) for each wireless channel. The carrier frequency, which can carry multiple wideband channels, has to be in the range of 20 GHz or above. Therefore, a broadband spectrum is required in order to build this information superhighway. The higher the frequency, the more difficult it is for the radio wave to reach the customer. Thus, mother nature limits the utilization of wide bandwidths for the information superhighway. Mobility in the information superhighway presents another difficulty in wireless.

The means for deploying the broadband channels for the information superhighway systems are by a microwave link and an infrared link. The spectrum of the radio and infrared bands is illustrated in Fig. 17.10.

The advantages of using a microwave system are:

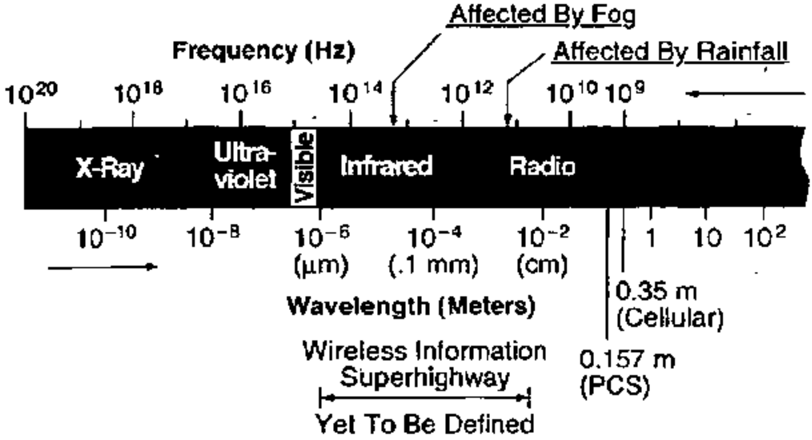


Figure 17.10 Radio and infrared bands.

1. The system does not require line-of-sight conditions for reception.
2. Broadband signal provides less fading.
3. The conventional diversity schemes can further reduce fading.
4. Can apply CDMA scheme for long-range transmission.

The disadvantages of using a microwave system are:

1. The noise floor is relatively high.
2. The propagation loss is high.
3. Attenuation is affected mostly by rainfall.

The advantages of using an infrared link are:

1. Eavesdropping can be prevented.
2. It is highly directional.
3. It provides power conservation.
4. No license is required.
5. It is light weight.

The disadvantages of using an infrared link with today's technology are:

1. For short distances.
2. For mobile communications within rooms using diffused radiation which recreates multiple reflection waves to reach the terminals.

3. Most fixed-to-fixed communications are under the line-of-sight condition.
4. The conventional diversity schemes cannot help reduce fading.
5. Attenuation is affected mostly by fog.

The infrared wavelength is roughly between 0.1 mm to 1 μm. It attenuates heavily by the fog. At a half mile, the loss of over 60 dB is due to thick fog, 30 dB due to moderate fog, and 0 dB due to the thin fog. The background noises due to environment illumination are: (1) sunlight (daylight)—a high noise level at a wavelength less than 1.2 μm; (2) tungsten lamps; (3) fluorescent lamps; and (4) heaters. These noises can produce DC and low frequency photocurrents and generate shot noise in the photodetector. Also, the rapidly fluctuating components associated with higher harmonic of the main frequency emitted by some artificial light sources received by the photodetector. The

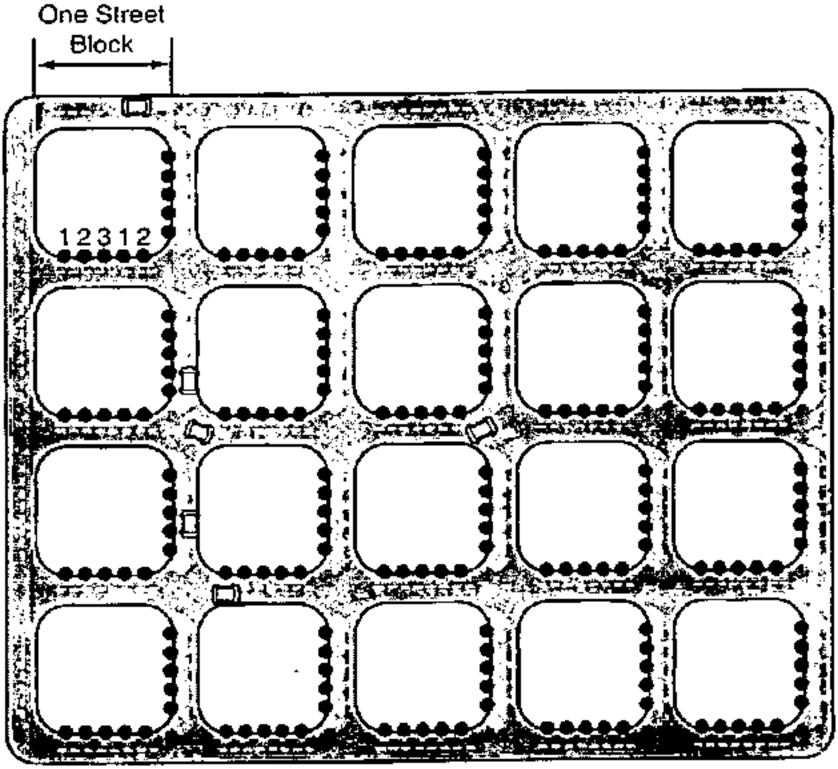


Figure 17.11 The information superhighway structure—along the city streets.

background noise can be reduced by the optical filters. (1) The interference filters (bandpass) which transmission coefficient is less than 40%, optical response changes with angle of incidence of light and cost is high. (2) Absorption filters which noise reduction is 54% for fluorescent tubes, depends on the choice of absorbing material and cost is low.

In the mobile application, we are using diffuse and quasi-diffuse transmission. In diffuse transmission, use sufficient emitted optical power for covering the multipath dispersion, create reflections, and create multi-beams in wireless-transmission configurations. In the quasi-diffuse transmission, the photodetector receives and the laser or LED emits from and to the remote station (RS). Then the common node (CN) and RS are in a line-of-sight condition. All the RS are aiming at CN which is the control center.

Among these difficulties the weather, as mentioned above, introduces undesirable factors to the higher band microwave frequencies or to optical frequencies. Therefore, combining the two systems—the infrared system which is affected by fog, but not affected by rainfall and the microwave system which is affected just the opposite—can achieve multi-propagation-medium diversity. The experiment has been carried out and stated in Sec. 18.4. With that, the airlink for providing the wireless information superhighway system may barely reach 50 meters which is our goal.

The most difficult part of developing the wireless information superhighway is the last 50 meters. Due to the requirements of the wide bandwidth, future technology for the last 50 meters should utilize microwave and infrared, and intelligent cell technologies to obtain the wireless information superhighway. However, more research needs to be conducted in this area. The future wireless information superhighway, thus, has to be hybrid with the wireline information superhighway whose transmission medium uses non-interference wideband optical fiber. For personal mobility and personal communications, the wireless information superhighway will add great value in the entire information superhighway system. We may illustrate an application of using the last 50 meters.

17.6.1 An example for applying the last 50 meters

A wireless information superhighway structure along city streets can be provided as shown in Fig. 17.11. In order to only concentrate on the last 50 meter link, the means of delivering the broadband signal from a distant source will lean on the optical fiber. In the last 50 meters, the microwaves or infrared, and the intelligent microcell can

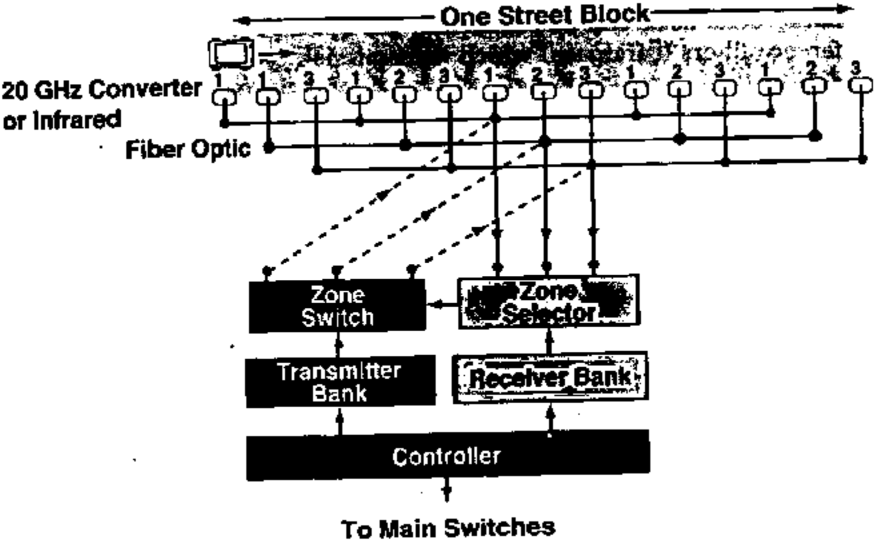


Figure 17.12 Microcell application for information superhighway.

help provide the link along each street block as shown in Fig. 17.12. The signal is delivered via optical fibers to the zone sites along the street. At the zone sites, the signal can be converted to infrared radiation or microwave transmission. The intelligent microcell technology stated in Sec. 16.2 will be applied to convey the signal from the three-zone site to the mobile unit. The range is within 50 meters. The three-zone selectors detect the signal at each zone. For instance, if the signal at zone 1 is strong, all the zone 1's are turned on. Since the power is very low, no interference would occur at the other neighboring streets. Then the mobile unit traveling along the whole block of the street will keep the same channel, but the zone sites along the street will turn on and turn off as the location of the mobile unit changes. No handoff takes place along the whole street block. This arrangement can ease the load of mobile switching for handoffs and provide more capacity to receive the new calls. Also, this arrangement can reduce the number of zone selectors to only one. This illustration of wireless information superhighway system needs a lot of research effort to make it happen.

References

1. R. B. Robrock II, "The Intelligent Network," *Proc. IEEE,* vol. 75, no. 1, Jan. 1991, pp. 7–20.

2. R. K. Berman, J. H. Brewster, "Perspective on the AIN Architecture," *IEEE Communications Magazine,* vol. 31, February 1993, pp. 27–33.
3. D. A. Pezzutti, "Operations Issues for Advanced Intelligent Networks," *IEEE Communications Magazine,* Feb. 1992, pp. 58–63.
4. A. R. Modarressi, "Signaling System No. 7: A Tutorial," *IEEE Communications Magazine,* July 1990, pp. 19–35.
5. H. Rarig, "ISDN Signal Distribution Network," *IEEE Communications Magazine,* vol. 32, June 1994, pp. 34–38.
6. K. Murano, K. Murakami, E. Iwabuchi, T. Katsuki, H. Ogasawara, "Technologies Towards Broadband ISDN," *IEEE Communications Magazine,* vol. 28, April 1990, pp. 66–70.
7. T. H. Wee, "Cost-Effective Network Evolution," *IEEE Communications Magazine,* Sept. 1993, pp. 64–73.
8. M. Hibino, F. Kaplan, "User Interface Design for SONET Networks," *IEEE Communications Magazine,* vol. 30, August 1992, pp. 24–27.
9. B. Jabbain, "Intelligent Network Concepts in Mobile Communications," *IEEE Communications Magazine,* vol. 31, February 1992, pp. 64–69.
10. A. S. Acampora and M. Naghshinch, "Control and Quality-of-service Provisioning in High-speed Microcellular Network," *IEEE Personal Communications,* vol. no. 2, April, 1994, pp. 36–43.
11. D. J. Goodman, G. P. Pollini, and K. S. Meier-Hellstern, "Network Control for Wireless Communications," *IEEE Communications Magazine,* Dec. 1992, pp. 116–125. W. T. Webb, "Modulation Methods for PCNs," *IEEE Communications Magazine,* Dec. 1992, pp. 90–95.
12. A. Nakajima, M. Eguchi, T. Arita, and H. Takeda, "Intelligent Mobile Communications Network Architecture," *Proceeding of ISS '90,* Stockholm, Sweden, May 1990.
13. I. W. Habib, T. N. Saadawi, "Controlling Flow and avoiding Congestion in Broadband Networks," *IEEE Communications Magazine,* October 1991, vol. 29, pp. 46–53.
14. A. A. Lazar, G. Pacifici, "Control of Resources in Broadband Networks With Quality of Service Guarantees," *IEEE Communications Magazine,* October 1991, vol. 29, pp. 66–73.
15. Y. Inoue, N. Terada, "Granulated Broadband Network," *IEEE Communications Magazine,* April 1994, pp. 56–63.
16. K. Sato, S. Ohta, I. Tokizawa, "Broadband ATM Network Architecture Based on Virtual Paths," *IEEE Transactions on Communication,* August 1990.
17. P. Newman, "ATM Local Area Networks," *IEEE Communications Magazine,* vol. 32, March 1994, pp. 86–98.
18. S. Isaku, M. Ishikura, "ATM Network Architecture for Supporting the Connectionless Service," *Proc. IEEE Infocom,* vol. 2, pp. 796–802, San Francisco, June 1990.
19. K. Kato, T. Shimoe, K. Hajikano, K. Murakami, "Experimental Broadband ATM Switching System," *Proc. Globecom '88,* pp. 1288–1292.
20. J. A. McEachern, "Gigabit Networking on the Public Transmission Network," *IEEE Communications Magazine,* vol. 30, April 1992, pp. 70–78.
21. E. W. Zegma, "Architecture for ATM Switching Systems," *IEEE Communications Magazine,* vol. 31, February 1993, pp. 28–37.
22. P. Condreuse, M. Servel, "Prelude: An Asynchronous Time-Division Switched Network," *Proc. Intl. Communication Conference,* June 1987, pp. 769–773.
23. P. Gardenier, M. Shafi, R. B. Vernall, M. Milner, "Sharing Issues Between FPLMTS and Fixed Services," *IEEE Communications Magazine,* vol. 32, June 1994, pp. 74–78.
24. R. Steele, "The Evolution of Personal Communications," *IEEE Personal Communications,* April 1994, pp. 6–11.

Chapter

18

Cellular Related Topics

18.1 Study of a 60-GHz Cellular System

A series of studies[1,2] have explored the implementation of a 60-GHz mobile telephone system using direct line-of-sight transmission along urban streets. Use of the 60-GHz band is encouraged for the following reasons.

1. The 60-GHz band is in the oxygen-absorption range. In this range the attenuation of radio signals in the oxygen-absorption band is two orders of magnitude greater than the attenuation outside the oxygen-absorption band over a 1-km distance. Therefore, the 60-GHz band cannot be used by many applications; however, if it is properly implemented, it can be allocated to a cellular mobile radio system. The FCC may be glad to give this band away.
2. The characteristics of this high-attenuation signal over the propagation path create a natural barrier to cochannel or adjacent-channel interference in the cellular mobile system.

18.1.1 Propagation in the scattered environment

In the UHF range or at X band, multipath signal scattering from vehicles and buildings in the mobile radio environment has frequently caused deep and rapid fading of the received signals. Sometimes, the signal can be received by propagation through scattered or reflected signals, a natural phenomenon. However, when a 60-GHz band is used, line-of-sight propagation is required. A series of experiments at 59.5 GHz were carried out in 1972 in urban areas.[2]

The average output power at the mobile antenna was 40 mW (16 dBm), and the parabola antenna beamwidths were 3° at both the base station and mobile ends. The data were collected on three streets in Red Bank, New Jersey. The streets were chosen because they were representative of the urban mobile environment and were at least 0.5 mi long.

18.1.2 Fixed terminals

The mobile transmitter and the mobile receiver were parked about 0.56 km (0.35 mi) apart on opposite sides of a street. The results for each street are plotted in Fig. 18.1. Fades exceeding 3 dB occurred 5 percent of the time on Monmouth Street, 20 percent of the time on Bridge Street, and 34 percent of the time on Broad Street. The measuring limit was at −52 dBm, which presents a signal fade of 15 dB. Fades exceeding this limit occurred 1 percent of the time on Bridge Street, 2 percent of the time on Monmouth Street, and 3 percent of the time on Broad Street. Fades exceeding 15 dB were caused by large trucks or buses completely blocking the path within 30 m (100 ft) of the transmitter or receiver.

18.1.3 Moving terminal

The mobile receiver was parked at the side of the street, and the mobile transmitter started at least 0.8 km (0.5 mi) from the receiver and

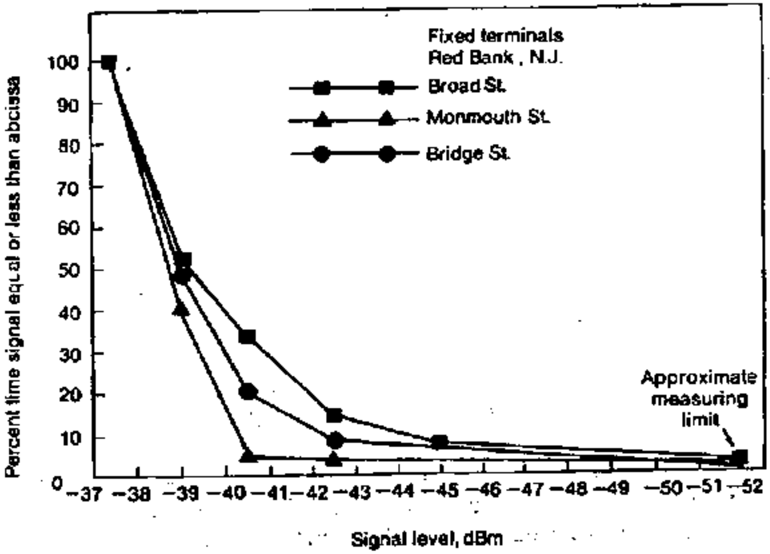


Figure 18.1 Fading statistics from fixed terminals, Red Bank, N.J. (*From Ref.* 2.)

proceeded toward and past the receiver at a constant speed of 24 km/h (15 mi/h). The results are plotted in Fig. 18.2. The fading statistics of all three streets are roughly the same. The fades exceeded 3 dB about 70 percent of the time. The fades exceeding the −52-dBm measuring limit (15 dB fades) occurred 9 percent of the time on Broad and Monmouth Streets but only 5 percent on Bridge Street because the line-of-sight signal was blocked by large trucks or buses. The Doppler frequencies ranged from a few hertz to 170 Hz. When vehicle speed was 15 mi/h the fading rate was 25 Hz. Fades exceeding 10 dB occurred 20 percent of the time. A typical run measured on Monmouth Street is shown in Fig. 18.3.

The experiments at 60 GHz reveal that the amplitude of the scattered signal was small in comparison to the direct signal. The effect of the scattered signal is small. The fading observed was neither deep nor rapid.

18.1.4 System consideration

From the preceding data, we may note the following problems in a 60-GHz mobile radio system: (1) the excessive propagation loss, (2) the pointing mechanism of the antennas, (3) the small separation between repeaters, and (4) the ways of avoiding line-of-sight blockage from large trucks and buses.

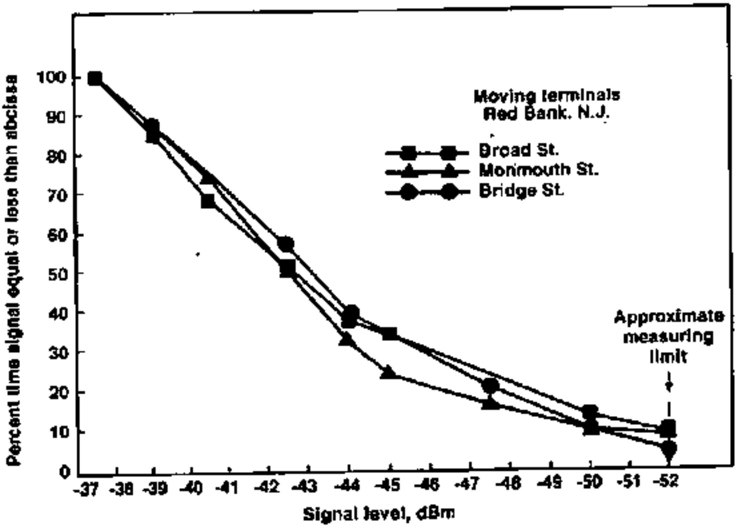


Figure 18.2 Fading statistics from moving terminals, Red Bank, N.J. (*From Ref.* 2.)

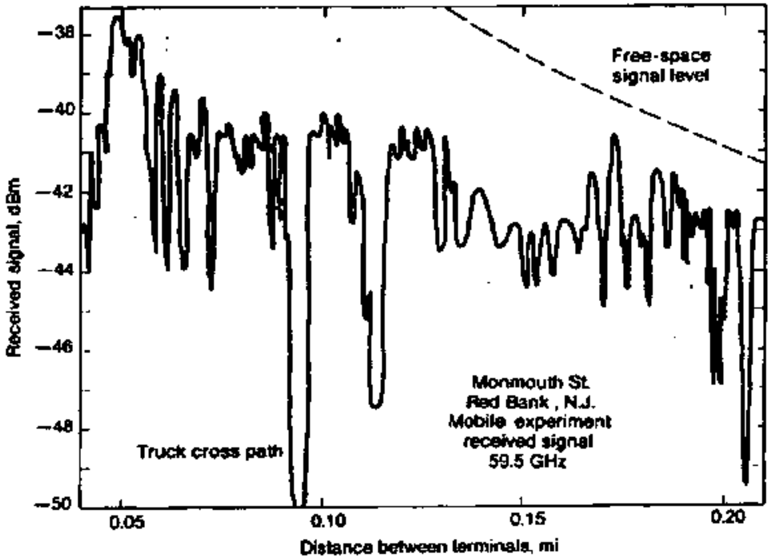


Figure 18.3 Received signal at Monmouth Street, Red Bank, N.J. (*From Ref.* 2.)

18.2 Cellular Fixed Stations

18.2.1 Radios for fixed-station telecommunications

Many alternatives can be used in the installation of radios in fixed-station telecommunications.[3] The cellular fixed station, one of these alternatives, is installed according to certain specifications.

1. To ensure a sufficient number of radio channels, each radio channel is assigned to a customer on a permanent basis.
2. When the number of available (unoccupied) radio channels is limited, two approaches can be used. The trunking approach is used to scan for an available channel and a set-up channel is used to initiate a call, and the call is then transferred to and carried on an assigned voice channel.
3. For cellular fixed ratios, the limited radio channels should be reused. Entire control functions are the same for fixed cellular systems as for other cellular mobile systems.

18.2.2 Two approaches for fixed cellular systems

The fixed cellular concept is not a new one. The implementation of 800-MHz technology has gradually reduced the cost of cellular components, and the fixed cellular system could provide an economic means of providing telephone coverage in a rural area.

There are two approaches to implementation of fixed cellular systems.

1. Use cellular mobile equipment for the fixed cellular stations. It may save the cost of manufacturing a new fixed cellular radio. No new spectrum would be needed.
2. Design a cellular fixed radio.
   a. Operation of this radio could be integrated with local telephone company switching offices (see Fig. 18.4*a*). However, a new spectrum would be needed.
   b. Operation of this radio could be integrated with cellular mobile switching; in such a case, no new spectrum would be needed.

18.2.3 Special features of fixed cellular systems

There are several advantages.

1. The cost of the radio is low because the logic unit is simpler.
2. Either regular switching or MTSO (mobile telephone switching office) switching can be used.
3. No handoff is needed.
4. Each link can be carefully engineered.
5. A cell with a large area can be served.
   a. Both antenna heights at two ends are high, and most links are line-of-sight links. The propagation loss approaches the free-space loss.
   b. There is no multipath fading. The required C/I for fixed cellular systems is $C/I \geqslant 10$ dB.
   c. The surroundings are quiet.
   d. Directional antennas can be used at the customer site.
6. A low-cost controller can be provided at either the cell site or the telephone company relay site.
7. The fixed cellular system will expect a longer holding time, and no calls will be dropped.
8. The busy periods (rush hours) in fixed cellular systems usage are different from those in mobile cellular system usage.
9. It is possible to use radio channels for data links between cell site and MTSO.

18.2.4 Design of a cellular fixed system

Because fixed cellular stations cover larger areas, the system can cover a 40-mi-radius cell ($R = 40$ mi) or larger. The frequencies used in the

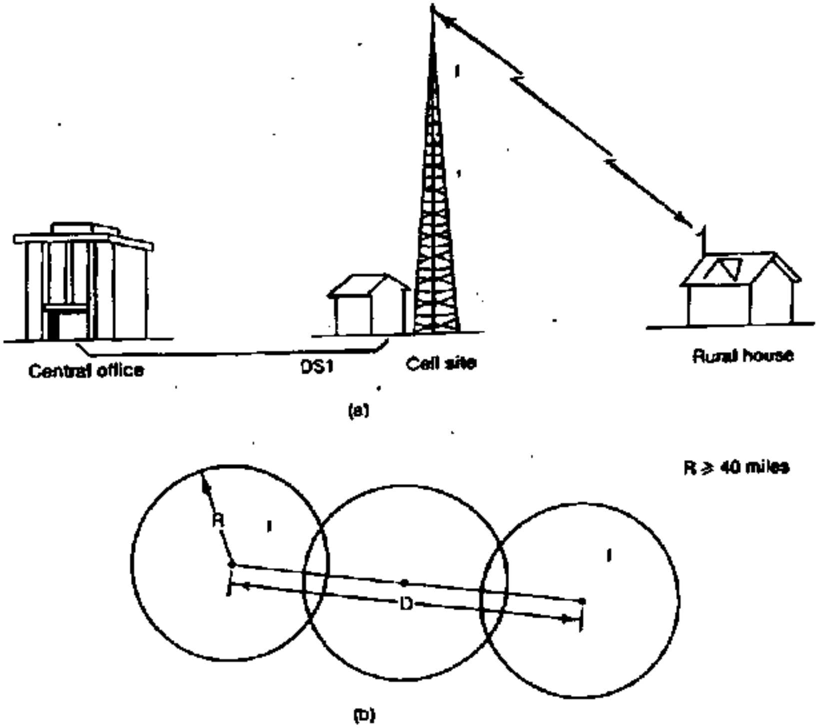


Figure 18.4 Fixed cellular system.

fixed cellular system can be identified as a subset $\{f_i\}$ of the total cellular mobile frequencies, say, 80 channels. The 80 channels need to be divided into only two groups, each with 40 channels. Each cell is assigned one group, and the other group is assigned to an adjacent cell. The separation between cochannel cells is $3R$ (see Fig. 18.1*b*). The reason for a closed cochannel cell separation is the natural isolation caused by the radio horizon phenomenon. The maximum area of each cell is

$$A = \pi(40)^2 = 5026 \text{ mi}^2$$

With 40 channels per cell, we can serve roughly 800 customers. If the area has to serve more customers, the size of the cells can be decreased.

18.3 Cellular Systems in Rural Service Areas[4]

Cellular mobile systems in the United States, roughly 733 market areas, have been designated as *cellular geographic service areas* (CGSA). Each CGSA can have block A systems and block B systems. The largest 305 cities of the 733 markets are called *metropolitan statistical areas* (MSAs) and the rest (428) are called *rural service areas* (RSAs). RSAs are usually adjacent to MSAs.

How to achieve a flexible and cost-effective cellular system design that will provide adequate RSA coverage but that will not interfere with MSA coverage is a challenging problem. In fact, there are three common obstacles.

1. RSA operators generally do not want to limit their design parameters.
2. MSA operators are afraid of the interference that might result from RSA service.
3. Any cell-site distance-separation specification might be adequate for one system (RSA or MSA) but not for the other.

Two approaches are recommended for controlling cochannel interference and adjacent-channel interference between RSA and MSA systems.

> Approach 1—create a buffer zone between the MSA and the RSA. The RSA will be mandated to limit its transmitted power and the antenna height at the RSA cell site so that they are compatible with the MSA specifications. (See Fig. 18.5.)

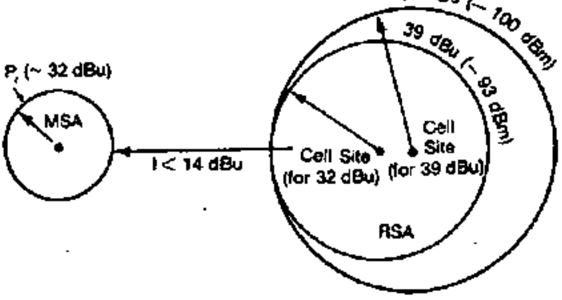


Figure 18.5 Received signal-strength power of an RSA.

Approach 2—let the RSA system designer know both the MSA boundary and the carrier-to-interference ratio at the boundary before planning the system. This way the RSA system designer will know the received signal level at the RSA boundary adjacent to the MSA.

Approach 2 may be more suitable in real situations. Its methodology is as follows.

1. The MSA provides the boundary signal level requirement (level A) to the RSA (see Fig. 18.5).
2. The RSA system designer considers and designs the RSA system in accordance with MSA compatibility requirements.
3. The RSA can implement a signal level of −110 dBm at the boundary of the CGSA if there is no interference with the MSA.
4. The MSA and RSA system designers can consider what specifications will be compatible for both parties.

At the cell site, the RSA operator can install any kind of directional antenna and raise the antenna to maximize the transmitted power, provided the above requirements are satisfied. The directional antenna can also be used to reduce the interference to or from the other site.

There are a few additional considerations.

1. A low-cost antenna mast or an existing mast should be used.
2. Half of the unused voice channels could be used for microwave transmission.
3. The installation of small switching systems should be considered, or these systems could be shared with neighboring MSAs or RSAs.

18.4 Diversity Media System with Millimeter-Wave Link and Optical-Wave Link

18.4.1 Introduction

A diversity system with millimeter-wave and optical-wave links can be achieved.[5] The idea is based on the fact that the optical wave is primarily attenuated by fog[6] and the millimeter wave primarily by rain.[7] Since fog and rain usually do not occur at the same time, a diversity advantage using an optical-wave signal and a millimeter-wave signal may be realized.

For investigating the diversity advantage on these two links (optical wave and millimeter wave) in a metropolitan area, data on the signal attenuation by fog on an optical-wave link and data on the signal attenuation by rain on a millimeter-wave link over the same path simultaneously in that area was collected.

In 1973, an optical-wave (0.9 μm) link between the 88th floor of the Empire State Building and the 58th floor of the Pan American building (a distance of about 0.55 mi) was installed.[8] The data on signal attenuation by fog has been converted to a probability distribution curve (PDC), shown in Fig. 18.6. In addition, there are three other curves, one obtained at Holmdel, New Jersey, and two at the AT&T building in New York City, with different floor heights, also shown in

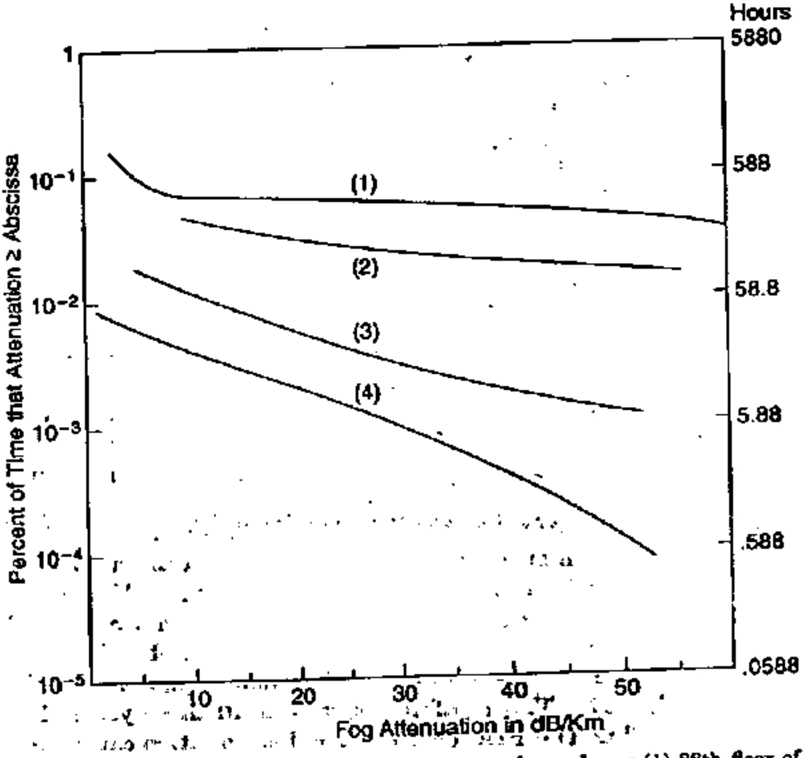


Figure 18.6 Optical signal attenuation by fog at various places: (1) 88th floor of Empire State Building—58th floor of Pan Am Building, New York City, 0.55 mi in distance (one-way transmission); (2) Radio Range Building, Bell Laboratories, Holmdel, N.J.; round-trip path is 300 ft; (3) 21st floor of AT&T Building—19th floor of Western Electric Building, New York City, roundtrip path is 240 ft; (4) 4th floor of AT&T Building—3rd floor of Western Electric Building, New York City, round-trip path is 240 ft.

Fig. 18.6 for comparison. We may note that the signal attenuation by fog is drastically changed by the height of the link.

A 3-mm link between the Empire State and Pan Am Buildings, using a 15-mW IMPATT diode as a source, two 30-in parabolic dish antennas (one transmitting and one receiving) for a link gain of 106 dB, and a Schottky-barrier diode for detection, was installed.[9] Limited data were collected to demonstrate that the link was clearly established. The 3-mm signal attenuation caused by rainfall in New York City should be acquired from other sources.

First, we assume that the effect on millimeter-wave signal attenuation of rainfall is small where the link is short. Using this assumption, we can then obtain the 3-mm-wave signal attenuation caused by rainfall over the Empire State–Pan Am link in New York City from some other nearby sources, such as the data collected at Central Park, Manhattan, or New York City.

Now there are two pieces of data: the optical-wave attenuation over the Empire State–Pan Am link and the millimeter-wave attenuation, which is based on the rainfall statistics at Central Park, Manhattan, and New York City. From these two pieces of data, a study of a diversity system consisting of a millimeter-wave link and an optical-wave link will carried out.

18.4.2 Comparison of two signal attenuations from their PDC curves

At first, we have to obtain an annual PDC of millimeter-wave attenuation caused by rainfall from a nearby location of the Empire State–Pan Am link. We know that the rain accumulation data at Central Park can be obtained from U.S. climatological data.[10] From the cumulative rain data, a distribution curve of rain rate versus time for each rainfall event can be generated.[11] The conversion from rain rate to signal attenuation has been obtained by several methods[6,12]; Oguchi's approximate method[12] provides a table that can easily be used. The PDC curves of 3-mm-wave attenuation (dB/km) in New York City calculated annually for three consecutive years are shown in Fig. 18.7. The details of how Fig. 18.7 was obtained are described in Ref. 4. In Fig. 18.7, we find that rainfall was slightly more frequent in 1971 and 1972 than in 1970. The rainfall statistics in all three years, 1970 to 1972, are similar. The PDC curve of signal attenuation caused by rain in 1972 was picked and compared with the PDC curve of signal attenuation caused by fog in our analysis. Comparing Fig. 18.6 with Fig. 18.7, we find that the optical wave is attenuated by fog more frequently than the millimeter wave is attenuated by rain.

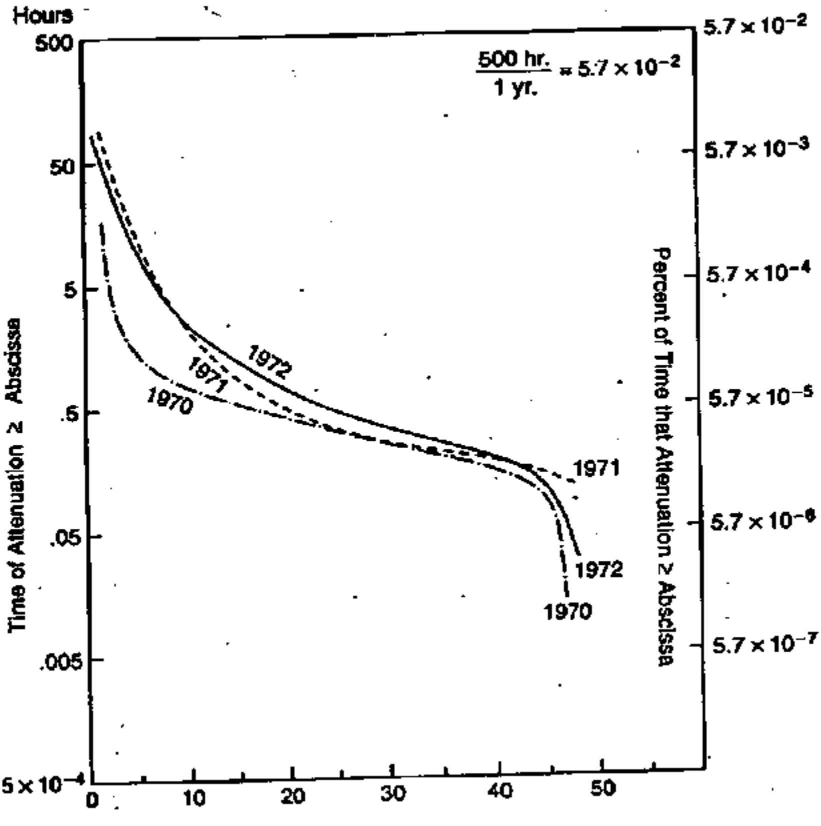


Figure 18.7 100-GHz signal attenuation by rain at Central Park, New York City.

Assuming that fog and rain do not occur simultaneously, then the PDC obtained from a selection-combining diversity signal between the millimeter and the optical wave is

$$P_C = P_r P_f \tag{18.4-1}$$

where P_r and P_f are PDC curves of signal attenuation caused by rainfall and fog respectively. P_r was obtained from Central Park and used for representing the signal attenuation by rain in the Manhattan area. Three selection-combining diversity signals can be obtained from Equation (18.4-1), one at Empire State–Pan Am, one at AT&T 21st

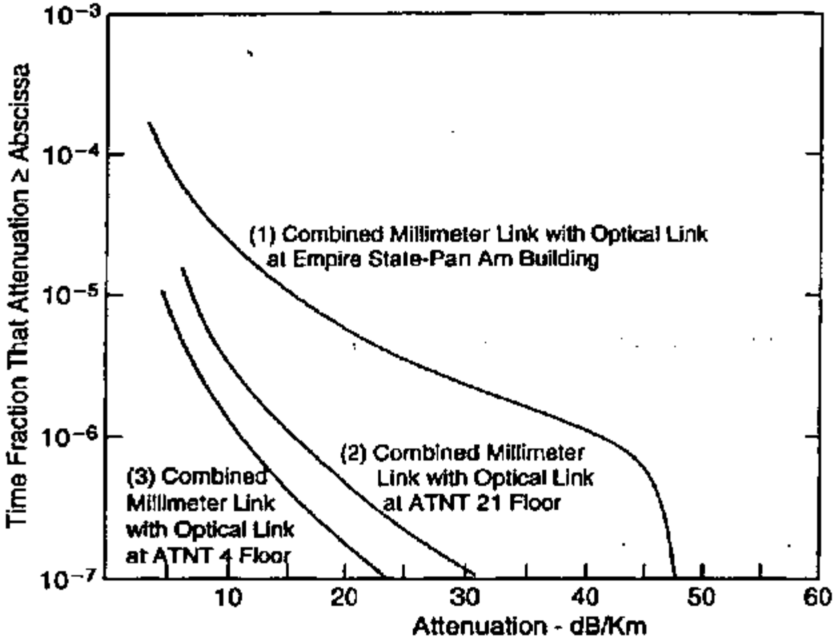


Figure 18.8 A predicted selection-combining signal between two frequencies in New York City.

floor, and one at AT&T 4th floor (Fig. 18.8). All three links are in the Manhattan area. The most advantageous outcome of using this millimeter wave–optical wave diversity scheme can be seen from the selection-combining diversity signal at AT&T 4th floor. We may conclude that a diversity system consisting of a millimeter-wave link and an optical-wave link is suitable for a site at a lower height above the ground.

18.5 Cellular Radio Telecommunications Intersystem Operations[13]

The purpose of having cellular radio telecommunications intersystem operations is to provide to cellular radio telephone subscribers certain services requiring interaction between different cellular systems. Because of the useful and effective services, we need standardized intersystem procedures. The standard is called IS-41B. There are five documents pertaining to the IS-41B as follows:

41.1B Function Overview

41.2B Intersystem Handoff

41.3B Automatic Roaming

41.4B Operative Administration and Maintenance

41.5B Data Communications

Each of these documents identifies its cellular services which require intersystem cooperation.

Standards setting is performed primarily by EIA/TIA with every effort expended to avoid arbitrary restrictions and to encourage innovative new services and capabilities by carriers and/or manufacturers based on market demands and evolving technology.

Restrictions on IS-41B

1. Voice facilities for intersystem handoff are restricted to direct dedicated circuits between pairs of participating systems.
2. When the CSS (cellular subscriber station) is in an alert state, handoffs between systems should not take place.
3. The flow control of data between applications is not provided in the data link and network layer portions of this protocol.
4. Call delivery provided only by means of employing a TLDN (temporary level directory number).
5. Full intersystem functionality does not exist and is being studied for future use.

18.5.1 Intersystem handoff

The intersystem handoff procedure is in the handoff sequence between two different mobile switching centers (MSCs). An intersystem handoff means to switch a CSS telephone call that is in progress on the "serving" MSC to a different MSC.

The dedicated voice circuits between two cooperating systems are used for the purpose of continuing speech transmission after an intersystem handoff is completed. This is currently an IS-41B restriction. A data link connection must be established between the cooperating systems. The physical layer of the data link is referred to as 41.5B. All the voice circuit control signaling such as circuit seizure, release, etc., shall be performed by signaling on the data link. The data link can use either signaling X.25 or SS7.

Intersystem handoff procedures. There are three phases to the intersystem handoff procedure as follows:

1. Location Phase: The serving MSC system makes a handoff measurement request to the candidate MSC systems and determines the target MSC system among them from the handoff measurement reply.
2. Handoff Phase: The servicing MSC initiates a handoff (either on the handoff-forward, handoff-back, or handoff-to-third) to the target MSC, then the target MSC accepts one of these handoff.
3. Release Phase: The initiating MSC releases a handoff request, then the receiving MSC completes the handoff handling.

A call can be engaged in more than two MSCs, then the path minimization is used to keep the number of MSCs involved in a call to a minimum. Then the handoff procedures can be applied to consecutive inter-MSC handoffs for the same CSS call.

18.5.2 Intersystem roaming

The purpose of IS-41.3B is to provide "automatic roaming" as one of several features as follows:

1. Making the identity of the current serving or visited system known to the home system.
2. Establishing financial responsibilities for the roaming subscriber. The subscriber is notified of the charge for the equipment rental after each call.
3. Establishing a valid roamer service profile in a visited system can eliminate fraudulent calls.

The dedicated voice circuits between cooperating MSCs are provided for the purpose of delivering an incoming call to the cellular subscriber while in a visited system. A data link connection must be established between the cooperating cellular network elements. The procedures leading to providing routing information of calls to the roaming subscriber in question shall be performed by signaling on the data link.

Automatic roaming procedures. The MSC detecting foreign mobile registration procedure leads to a registration notification that includes autonomous registration, call origination, call termination, or other mechanisms.

If the received message from the CSS cannot be processed, then the VLR or HLR "receiving registration notification invoke" begins. When roaming is not valid, registration cancellation goes into affect. There are several features and requests listed as follows:

Remote feature control

1. MSC detecting remote feature control access
2. VLR receiving remote feature control request invoke
3. HLR receiving remote feature control request invoke

Requests from the CSS's original HLR

1. Location/routing request
2. Call data/routing request
3. Transfer-to-number request
4. Service profile request
5. Qualification request

18.5.3 OA&M (operation, administration and maintenance) and data link

OA&M permits cellular operators to operate, administrate and maintain data communications for roaming, data link, and voice circuits for handoff between two different systems. The functions of OA&M are:

1. The network performance features
2. Abnormal conditions
3. Failure to receive
4. Unreliable roamer data
5. Inter-MSC trunk testing

Data links use the standardized protocols so that a minimum of prior coordination between two mobile systems is necessary to communicate. The OSI protocol is used for mobile application described in Chap. 17. Evaluation of network connectivity, service provided and intersystem capabilities implies that the protocol should support online negotiation of protocol features.

References

1. C. L. Ruthruff, "A 60 GHz Cellular System," Microwave Mobile Symposium, Boulder, Colorado, 1974.
2. L. U. Kibler, "A 60 GHz Propagation Measurement," Microwave Mobile Symposium, Boulder, Colorado, 1974.

3. FCC's Notice of Proposed Rulemaking on Establishing Basic Exchange Telecommunications Radio Service," Communications Commission Docket No. 86-495, January 16, 1987.
4. W. C. Y. Lee, "Cellular Technology for Rural Areas," *Communications,* November 1987, p. 78.
5. L. C. Tillotson, "Customer-To-Customer Via Millimeter Wave," private communication, June 26, 1972.
6. C. L. Ruthroff, "Rain Attenuation and Radio Path Design," *Bell System Technical Journal,* vol. 49, pp. 121–136, January 1970.
7. T. S. Chu and D. C. Hogg, "Effects of Precipitation on Propagation at 0.63, 3.5, 10.6 Microns" *Bell System Technical Journal,* May–June 1968, pp. 723–759.
8. H. J. Schulte, "Optical-Wave Link Setup," private communication, 1973.
9. W. C. Y. Lee, "Millimeter-Wave Link Setup," private communication, 1973.
10. U.S. Dept. of Commerce, "Climatological Data, Annual," published once a year.
11. W. C. Y. Lee, "An Approximate Method for Obtaining Rain Rate Statistics for Use in Signal Attenuation Estimating", *IEEE Trans. on Antennas and Propagation,* vol. AP-27, May 1979, pp. 407–413.
12. T. Oguchi, "Attenuation of Electromagnetic Wave Due to Rain With Distorted Raindrops (Part II)," *Journal of Radio Research Lab,* Tokyo, vol. II, pp. 19–44, January 1964.
13. EIA/TIA, "Cellular Radio-Telecommunication Intersystem Operations," Interim Standard, Eng. Dept. EIA, December 1991, distributed by Global Engineering Documents, Irvine, California.