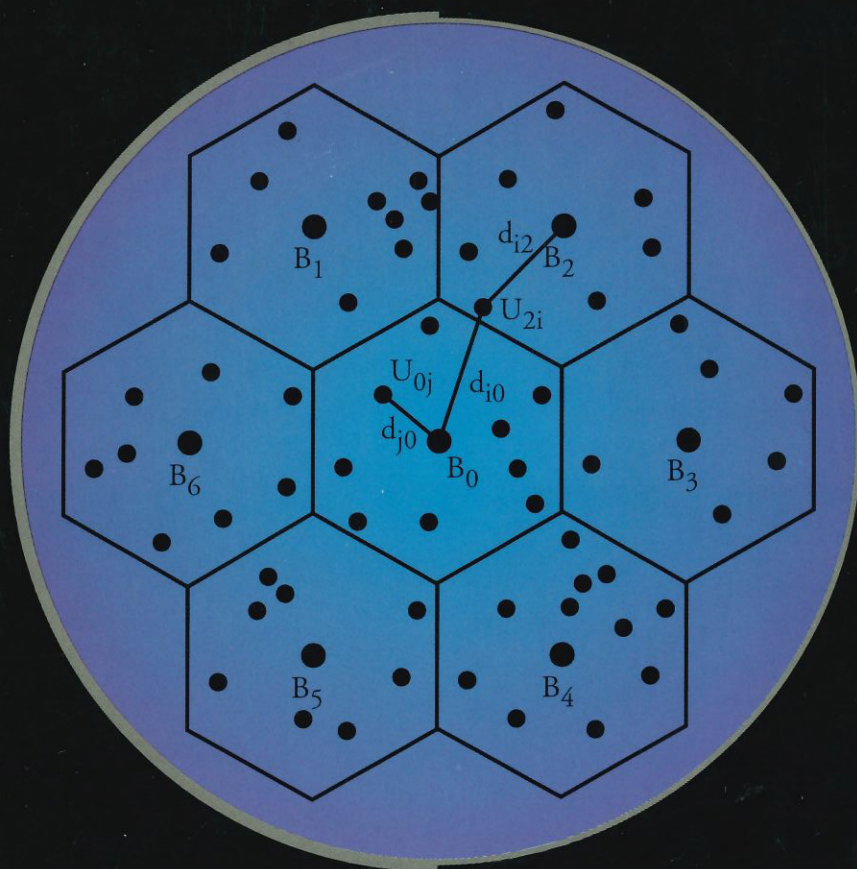


# WIRELESS

communications

Principles & Practice



Theodore S. Rappaport

# Wireless Communications

*Principles and Practice*

**Theodore S. Rappaport**



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## Multiple Access Techniques for Wireless Communications

**M**ultiple access schemes are used to allow many mobile users to share simultaneously a finite amount of radio spectrum. The sharing of spectrum is required to achieve high capacity by simultaneously allocating the available bandwidth (or the available amount of channels) to multiple users. For high quality communications, this must be done without severe degradation in the performance of the system.

### 8.1 Introduction

In wireless communications systems, it is often desirable to allow the subscriber to send simultaneously information to the base station while receiving information from the base station. For example, in conventional telephone systems, it is possible to talk and listen simultaneously, and this effect, called *duplexing*, is generally required in wireless telephone systems. Duplexing may be done using frequency or time domain techniques. *Frequency division duplexing* (FDD) provides two distinct bands of frequencies for every user. The forward band provides traffic from the base station to the mobile, and the reverse band provides traffic from the mobile to the base. In FDD, any *duplex channel* actually consists of two simplex channels, and a device called a *duplexer* is used inside each subscriber unit and base station to allow simultaneous radio transmission and reception on the duplex channel pair. The frequency split between the forward and reverse channel is constant throughout the system, regardless of the particular channel being used. *Time division duplexing* (TDD) uses time instead of frequency to provide both a forward and reverse link. If the time split between the forward and reverse time slot is small, then the transmission and reception of data appears simultaneous to the user. Figure 8.1 illustrates FDD and TDD

techniques. TDD allows communication on a single channel (as opposed to requiring two simplex or dedicated channels) and simplifies the subscriber equipment since a duplexer is not required.

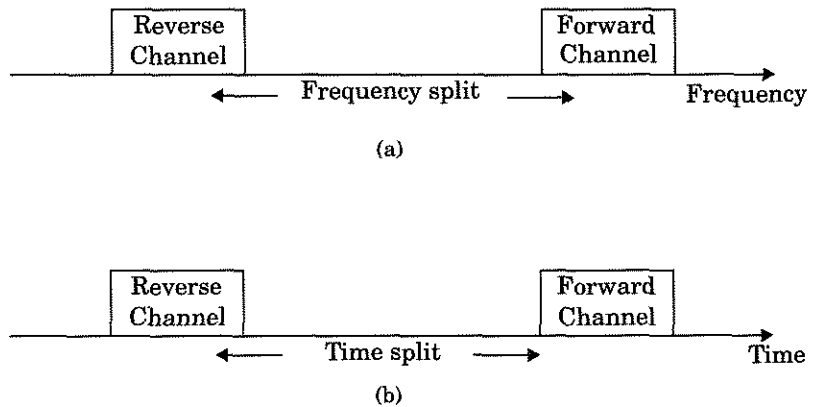


Figure 8.1

(a) FDD provides two simplex channels at the same time.

(b) TDD provides two simplex time slots on the same frequency.

There are several trade-offs between FDD and TDD approaches. FDD is geared toward radio communications systems that provide individual radio frequencies for each user. Because each transceiver simultaneously transmits and receives radio signals which vary by more than 100 dB, the frequency allocation used for the forward and reverse channels must be carefully coordinated with out-of-band users that occupy spectrum between these two bands. Furthermore, the frequency separation must be coordinated to permit the use of inexpensive RF technology. TDD enables each transceiver to operate as either a transmitter or receiver on the same frequency, and eliminates the need for separate forward and reverse frequency bands. However, there is a time latency due to the fact that communications is not full duplex in the truest sense.

### 8.1.1 Introduction to Multiple Access

Frequency division multiple access (FDMA), *time division multiple access* (TDMA), and *code division multiple access* (CDMA) are the three major access techniques used to share the available bandwidth in a wireless communication system. These techniques can be grouped as *narrowband* and *wideband* systems, depending upon how the available bandwidth is allocated to the users. The duplexing technique of a multiple access system is usually described along with the particular multiple access scheme, as shown in the examples below.

**Narrowband Systems** — The term *narrowband* is used to relate the bandwidth of a single channel to the expected coherence bandwidth of the channel. In a narrowband multiple access system, the available radio spectrum is

divided into a large number of narrowband channels. The channels are usually operated using FDD. To minimize interference between forward and reverse links on each channel, the frequency split is made as great as possible within the frequency spectrum, while still allowing inexpensive duplexers and a common transceiver antenna to be used in each subscriber unit. In narrowband FDMA, a user is assigned a particular channel which is not shared by other users in the vicinity, and if FDD is used (that is, each channel has a forward and reverse link), then the system is called FDMA/FDD. Narrowband TDMA, on the other hand, allows users to share the same channel but allocates a unique time slot to each user in a cyclical fashion on the channel, thus separating a small number of users in time on a single channel. For narrowband TDMA, there generally are a large number of channels allocated using either FDD or TDD, and each channel is shared using TDMA. Such systems are called TDMA/FDD or TDMA/TDD access systems.

**Wideband systems** — In wideband systems, the transmission bandwidth of a single channel is much larger than the coherence bandwidth of the channel. Thus, multipath fading does not greatly affect the received signal within a wideband channel, and frequency selective fades occur in only a small fraction of the signal bandwidth. In wideband multiple access systems, the users are allowed to transmit in a large part of the spectrum. A large number of transmitters are also allowed to transmit on the same channel. TDMA allocates time slots to the many transmitters on the same channel and allows only one transmitter to access the channel at any instant of time, whereas spread spectrum CDMA allows all of the transmitters to access the channel at the same time. TDMA and CDMA systems may use either FDD or TDD multiplexing techniques.

In addition to FDMA, TDMA, and CDMA, two other multiple access schemes are used for wireless communications. These are *packet radio* (PR) and *space division multiple access* (SDMA). In this chapter, the above mentioned multiple access techniques, their performance, and their capacity in digital cellular systems are discussed. Table 8.1 shows the different multiple access techniques being used in various wireless communications systems.

## 8.2 Frequency Division Multiple Access (FDMA)

Frequency division multiple access (FDMA) assigns individual channels to individual users. It can be seen from Figure 8.2 that each user is allocated a unique frequency band or channel. These channels are assigned on demand to users who request service. During the period of the call, no other user can share the same frequency band. In FDD systems, the users are assigned a channel as a pair of frequencies; one frequency is used for the forward channel, while the other frequency is used for the reverse channel. The features of FDMA are as follows:

- The FDMA channel carries only one phone circuit at a time.

**Table 8.1 Multiple Access Techniques Used in Different Wireless Communication Systems**

| Cellular System                            | Multiple Access Technique |
|--------------------------------------------|---------------------------|
| Advanced Mobile Phone System (AMPS)        | FDMA/FDD                  |
| Global System for Mobile (GSM)             | TDMA/FDD                  |
| U.S. Digital Cellular (USDC)               | TDMA/FDD                  |
| Japanese Digital Cellular (JDC)            | TDMA/FDD                  |
| CT2 (Cordless Telephone)                   | FDMA/TDD                  |
| Digital European Cordless Telephone (DECT) | FDMA/TDD                  |
| U.S. Narrowband Spread Spectrum (IS-95)    | CDMA/FDD                  |

- If an FDMA channel is not in use, then it sits idle and cannot be used by other users to increase or share capacity. It is essentially a wasted resource.
- After the assignment of a voice channel, the base station and the mobile transmit simultaneously and continuously.
- The bandwidths of FDMA channels are relatively narrow (30 kHz) as each channel supports only one circuit per carrier. That is, FDMA is usually implemented in narrowband systems.
- The symbol time is large as compared to the average delay spread. This implies that the amount of intersymbol interference is low and, thus, little or no equalization is required in FDMA narrowband systems.
- The complexity of FDMA mobile systems is lower when compared to TDMA systems, though this is changing as digital signal processing methods improve for TDMA.
- Since FDMA is a continuous transmission scheme, fewer bits are needed for overhead purposes (such as synchronization and framing bits) as compared to TDMA.
- FDMA systems have higher cell site system costs as compared to TDMA systems, because of the single channel per carrier design, and the need to use costly bandpass filters to eliminate spurious radiation at the base station.
- The FDMA mobile unit uses duplexers since both the transmitter and receiver operate at the same time. This results in an increase in the cost of FDMA subscriber units and base stations.
- FDMA requires tight RF filtering to minimize adjacent channel interference.

**Nonlinear Effects in FDMA** — In a FDMA system, many channels share the same antenna at the base station. The power amplifiers or the power combiners, when operated at or near saturation for maximum power efficiency, are nonlinear. The nonlinearities cause signal spreading in the frequency domain and generate *intermodulation* (IM) frequencies. IM is undesired RF radiation which can interfere with other channels in the FDMA systems. Spreading of the spec-

trum results in adjacent-channel interference. Intermodulation is the generation of undesirable harmonics. Harmonics generated outside the mobile radio band cause interference to adjacent services, while those present inside the band cause interference to other users in the mobile system [Yac93].

### Example 8.1

Find the intermodulation frequencies generated if a base station transmits two carrier frequencies at 1930 MHz and 1932 MHz that are amplified by a saturated clipping amplifier. If the mobile radio band is allocated from 1920 MHz to 1940 MHz, designate the IM frequencies that lie inside and outside the band.

### Solution to Example 8.1

Intermodulation distortion products occur at frequencies  $mf_1 + nf_2$  for all integer values of  $m$  and  $n$ , i.e.,  $-\infty < m, n < \infty$ . Some of the possible intermodulation frequencies that are produced by a nonlinear device are

$$(2n + 1)f_1 - 2nf_2, (2n + 2)f_1 - (2n + 1)f_2, (2n + 1)f_1 - 2nf_2, \\ (2n + 2)f_2 - (2n + 1)f_1, \text{ etc. for } n = 0, 1, 2, \dots$$

Table E8.1 lists several intermodulation product terms.

Table E 8.1: Intermodulation Products

| $n = 0$ | $n = 1$ | $n = 2$ | $n = 3$ |
|---------|---------|---------|---------|
| 1930    | 1926    | 1922    | 1918    |
| 1928    | 1924    | 1920    | 1916    |
| 1932    | 1936    | 1940    | 1944*   |
| 1934    | 1938    | 1942*   | 1946*   |

The frequencies in the table marked with an asterisk (\*) are the frequencies that lie outside the mobile radio band.

The first U.S. analog cellular system, the *Advanced Mobile Phone System* (AMPS), is based on FDMA/FDD. A single user occupies a single channel while the call is in progress, and the single channel is actually two simplex channels which are frequency duplexed with a 45 MHz split. When a call is completed, or when a handoff occurs, the channel is vacated so that another mobile subscriber may use it. Multiple or simultaneous users are accommodated in AMPS by giving each user a unique channel. Voice signals are sent on the forward channel from the base station to mobile unit, and on the reverse channel from the mobile unit to the base station. In AMPS, analog narrowband frequency modulation (NBFM) is used to modulate the carrier. The number of channels that can be simultaneously supported in a FDMA system is given by

$$N = \frac{B_t - 2B_{\text{guard}}}{B_c} \quad (8.1)$$

where  $B_t$  is the total spectrum allocation,  $B_{\text{guard}}$  is the guard band allocated at the edge of the allocated spectrum, and  $B_c$  is the channel bandwidth.

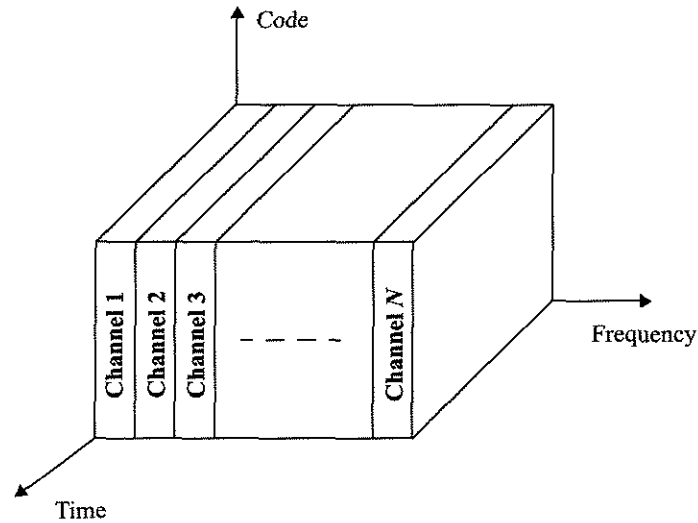


Figure 8.2  
FDMA where different channels are assigned different frequency bands.

### Example 8.2

If  $B_t$  is 12.5 MHz,  $B_{guard}$  is 10 kHz, and  $B_c$  is 30 kHz, find the number of channels available in an FDMA system.

### Solution to Example 8.2

The number of channels available in the FDMA system is given as

$$N = \frac{12.5 \times 10^6 - 2(10 \times 10^3)}{30 \times 10^3} = 416$$

In the U.S., each cellular carrier is allocated 416 channels.

## 8.3 Time Division Multiple Access (TDMA)

*Time division multiple access* (TDMA) systems divide the radio spectrum into time slots, and in each slot only one user is allowed to either transmit or receive. It can be seen from Figure 8.3 that each user occupies a cyclically repeating time slot, so a channel may be thought of as particular time slot that reoccurs every frame, where  $N$  time slots comprise a frame. TDMA systems transmit data in a buffer-and-burst method, thus the transmission for any user is noncontinuous. This implies that, unlike in FDMA systems which accommodate analog FM, digital data and digital modulation must be used with TDMA. The transmission from various users is interlaced into a repeating frame structure as shown in Figure 8.4. It can be seen that a frame consists of a number of slots. Each frame is made up of a preamble, information message, and trail bits. In a TDMA/TDD system, half of the time slots in the frame information message would be used for

the forward link channels and half would be used for reverse link channels. In TDMA/FDD systems, an identical or similar frame structure would be used solely for either forward or reverse transmission, but the carrier frequencies would be different for the forward and reverse links. In general, TDMA/FDD systems intentionally induce several time slots of delay between the forward and reverse time slots of a particular user, so that duplexers are not required in the subscriber unit.

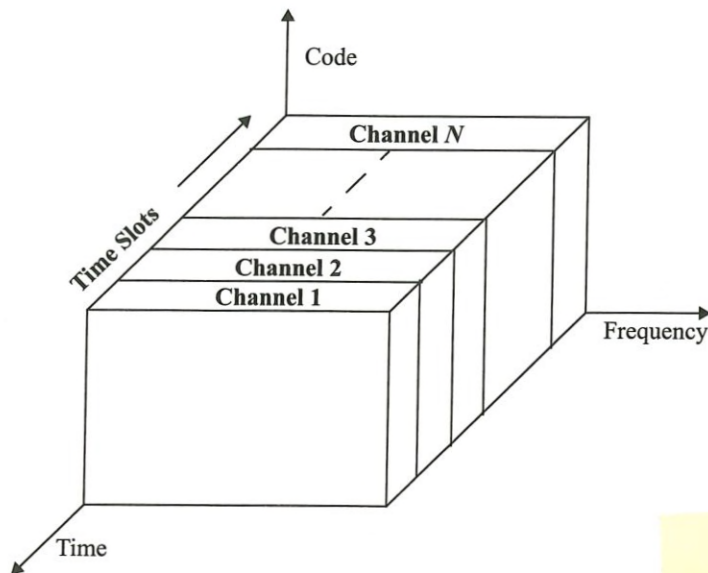


Figure 8.3

TDMA scheme where each channel occupies a cyclically repeating time slot.

TDMA frame  
preamble

In a TDMA frame, the preamble contains the address and synchronization information that both the base station and the subscribers use to identify each other. Guard times are utilized to allow synchronization of the receivers between different slots and frames. Different TDMA wireless standards have different TDMA frame structures, and some are described in Chapter 10. The features of TDMA include the following:

- TDMA shares a single carrier frequency with several users, where each user makes use of nonoverlapping time slots. The number of time slots per frame depends on several factors, such as modulation technique, available bandwidth, etc.
- Data transmission for users of a TDMA system is not continuous, but occurs in bursts. This results in low battery consumption, since the subscriber transmitter can be turned off when not in use (which is most of the time).
- Because of discontinuous transmissions in TDMA, the handoff process is much simpler for a subscriber unit, since it is able to listen for other base stations during idle time slots. An enhanced link control, such as that provided by *mobile assisted handoff* (MAHO) can be carried out by a subscriber

- by listening on an idle slot in the TDMA frame.
- TDMA uses different time slots for transmission and reception, thus duplexers are not required. Even if FDD is used, a switch rather than a duplexer inside the subscriber unit is all that is required to switch between transmitter and receiver using TDMA.
  - Adaptive equalization is usually necessary in TDMA systems, since the transmission rates are generally very high as compared to FDMA channels.
  - In TDMA, the guard time should be minimized. If the transmitted signal at the edges of a time slot are suppressed sharply in order to shorten the guard time, the transmitted spectrum will expand and cause interference to adjacent channels.
  - High synchronization overhead is required in TDMA systems because of burst transmissions. TDMA transmissions are slotted, and this requires the receivers to be synchronized for each data burst. In addition, guard slots are necessary to separate users, and this results in the TDMA systems having larger overheads as compared to FDMA.
  - TDMA has an advantage in that it is possible to allocate different numbers of time slots per frame to different users. Thus bandwidth can be supplied on demand to different users by concatenating or reassigning time slots based on priority.

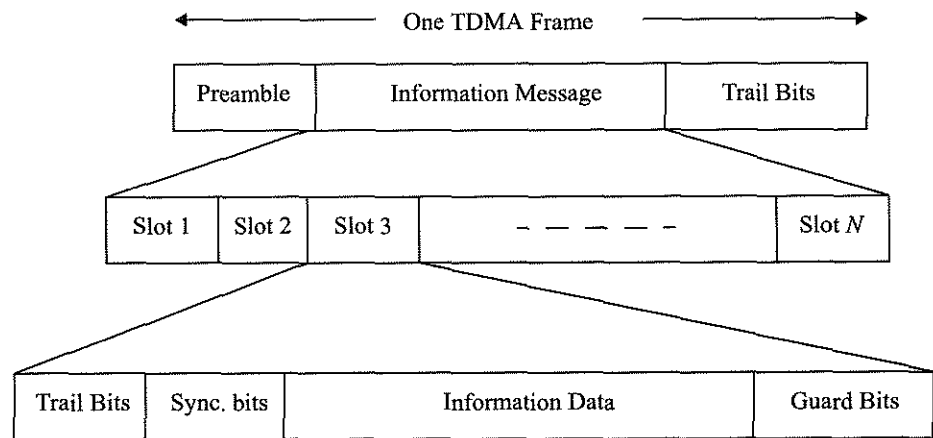


Figure 8.4  
TDMA frame structure.

**Efficiency of TDMA** — The efficiency of a TDMA system is a measure of the percentage of transmitted data that contains information as opposed to providing overhead for the access scheme. The frame efficiency,  $\eta_f$ , is the percentage of bits per frame which contain transmitted data. Note that the transmitted data may include source and channel coding bits, so the raw end-user efficiency of a system is generally less than  $\eta_f$ . The frame efficiency can be found as follows.

The number of overhead bits per frame is [Zie92],

$$b_{OH} = N_r b_r + N_t b_p + N_t b_g + N_r b_g \quad (8.2)$$

where,  $N_r$  is the number of reference bursts per frame,  $N_t$  is the number of traffic bursts per frame,  $b_r$  is the number of overhead bits per reference burst,  $b_p$  is the number of overhead bits per preamble in each slot, and  $b_g$  is the number of equivalent bits in each guard time interval. The total number of bits per frame,  $b_T$ , is

$$b_T = T_f R \quad (8.3)$$

where  $T_f$  is the frame duration, and  $R$  is the channel bit rate. The frame efficiency  $\eta_f$  is thus given as

$$\eta_f = \left(1 - \frac{b_{OH}}{b_T}\right) \times 100\% \quad (8.4)$$

**Number of channels in TDMA system** — The number of TDMA channel slots that can be provided in a TDMA system is found by multiplying the number of TDMA slots per channel by the number of channels available and is given by

$$N = \frac{m (B_{tot} - 2B_{guard})}{B_c} \quad (8.5)$$

where  $m$  is the maximum number of TDMA users supported on each radio channel. Note that two guard bands, one at the low end of the allocated frequency band and one at the high end, are required to ensure that users at the edge of the band do not “bleed over” into an adjacent radio service.

### Example 8.3

Consider Global System for Mobile, which is a TDMA/FDD system that uses 25 MHz for the forward link, which is broken into radio channels of 200 kHz. If 8 speech channels are supported on a single radio channel, and if no guard band is assumed, find the number of simultaneous users that can be accommodated in GSM.

### Solution to Example 8.3

The number of simultaneous users that can be accommodated in GSM is given as

$$N = \frac{25 \text{ MHz}}{(200 \text{ kHz})/8} = 1000$$

Thus, GSM can accommodate 1000 simultaneous users.

### Example 8.4

If GSM uses a frame structure where each frame consists of 8 time slots, and each time slot contains 156.25 bits, and data is transmitted at 270.833 kbps in the channel, find (a) the time duration of a bit, (b) the time duration of a slot, (c) the time duration of a frame, and (d) how long must a user occupying a single time slot must wait between two simultaneous transmissions.

## 8.8 Problems

- 8.1 The GSM TDMA system uses a 270.833 kbps data rate to support 8 users per frame. (a) What is the raw data rate provided for each user? (b) If guard time, ramp-up time, and synchronization bits occupy 10.1 kbps, determine the traffic efficiency for each user.
- 8.2 The U.S. Digital Cellular TDMA system uses a 48.6 kbps data rate to support 3 users per frame. Each user occupies 2 of the 6 time slots per frame. What is the raw data rate provided for each user?
- 8.3 For problem 8.2, assume each reverse channel frame contains 6 time slots with 324 bits per time slot, and within each time slot, assume there are 6 guard bits, 6 bits reserved for ramp-up, 28 synchronization bits, 12 control channel bits, 12 bits for supervisory control signals, and 260 data bits. (a) Determine the frame efficiency for the U.S. Digital Cellular standard. (b) If half-rate speech coding is used, then 6 users may be supported within a frame. Determine the raw data rate and frame efficiency for users with half-rate speech coding.
- 8.4 The Pacific Digital Cellular (PDC) TDMA system uses a 42.0 kbps data rate to support 3 users per frame. Each user occupies 2 of the 6 time slots per frame. (a) What is the raw data rate provided for each user? (b) If the frame efficiency is 80% and the frame duration is 6.667 ms, determine the number of information bits sent to each user per frame. (c) If half-rate speech coding is used, 6 users per frame are accommodated. Determine the number of information bits provided for each user per frame. (d) What is the information data rate per user in half-rate PDC?
- 8.5 Assume that a nonlinear amplifier is used to broadcast FDMA transmissions for the U.S. AMPS standard. If control channel 352 and voice channel 360 are simultaneously transmitted by a base station, determine all cellular channels on the forward link that might carry interference due to intermodulation.
- 8.6 If a paging system transmits at 931.9375 MHz, and a cellular base station broadcasts on AMPS control channel 318, and both antennas are co-located on the same broadcast tower, determine the cellular channels (if any) that may contain intermodulation interference, if detected by a receiver with a nonlinear amplifier. In what practical situations might intermodulation of this type be produced?
- 8.7 In an unslotted ALOHA system the packet arrival times form a Poisson process having a rate of  $10^3$  packets/sec. If the bit rate is 10 Mbps and there are 1000 bits/packet, find (a) the normalized throughput of the system, and (b) the number of bits per packet that will maximize the throughput.
- 8.8 Repeat problem 8.7 for a slotted ALOHA system.
- 8.9 Determine the propagation delay in packet transmission units if a 19.2 kbps channel data rate is used and each packet contains 256 bits. Assume a line-of-sight radio path exists for a user 10 km away from the transmitter. If slotted ALOHA is to be used, what is the best choice for the number of bits/packet for this system (assuming that 10 km is the maximum distance between the transmitter and receiver)?
- 8.10 Determine the number of analog channels per cell for the case of 7-cell reuse and  $n=3$  propagation path loss, where the minimum acceptable  $C/I = 14$  dB. Assume the channel bandwidth is 30 kHz and the total spectrum allocation is 20 kHz.
- 8.11 Repeat problem 8.10 for the cases where  $n = 2$  and  $n = 4$ .