CHANNEL CAPACITY

The present trend towards deregulation of telecommunications markets is spreading throughout the globe. Wireless technologies foster this transition due to their inherent cost structure and short infrastructure deployment times that allow new entrants to compete against entrenched wireline carriers. For a wireless operator, a critical factor to be competitive is both access to financing and availability of electromagnetic spectrum. The radio spectrum is a limited resource in high demand, traditionally regulated by government entities.

Wireless access systems demand sustained technological innovation to achieve robust communications channels and high-capacity systems able to handle high-density urban subscriber scenarios. Mounting requirements on capacity and data rates translate into demands for either more spectrum efficiency or more spectrum availability.

In this article we address channel capacity and its relationship with spectrum efficiency. Much inventive activity to date has gone into developing ways of serving more wireless subscribers within a given bandwidth. Depending on definition, channel capacity is a function of metrics. One can talk about capacity in terms of logical channels per base stations. Alternatively one can talk about metrics of Erlangs/MHz/sq. km. Each particular approach yields different results, the second one is more appropriate to explain frequency reuse via microcells. Spectrum reuse is also possible through better frequency planning.

The first section in this article addresses direct methods that can be used to maximize the amount of information per MHz that one device can send to another such as multiple access techniques, in particular, North American advanced mobile phone system, North American time-division multiple access, and North American code-division multiple access. Other direct techniques for increasing channel capacity are, for example, digital signal processing, improved receiver design, voice compression, and more efficient modulation schemes.

The section entitled "Frequency Reuse" deals with frequency planning and describes how a service provider that covers a wide area can geographically arrange network deployment to minimize mutual interference among cell sites and therefore improve overall system capacity. Other techniques to reduce capacity constraints due to co-channel interference include microcell technology, smart antennas, and co-channel interference cancellation.

The following section talks about capacity improvements through resource management techniques. Block allocation schemes based on fixed channel assignments (FCA) present capacity constraints due to trunking inefficiencies in permanent assignments. In contrast, dynamic channel assignment (DCA) is based on a pool of centralized resources. This section also addresses system capacity issues when multiple noncooperative devices or systems share the same bock of spectrum. These innovative policies are known as *open entry* or *open access* (1), which allow for multiple firms to compete in the provision of wireless services.

The penultimate section presents a discrete event simulation analysis applied to explore limitations and advantages of open-access DCA. Other topics are unlicensed PCS and the need for a spectrum etiquette.

The concluding section presents final remarks about channel capacity constraints.

DIRECT METHODS AND MULTIPLE ACCESS

This section describes techniques that can be used to maximize the amount of information per MHz carried over a given spectrum bandwidth. Direct methods for increasing channel capacity rely on technical improvements such as multiple access techniques, digital signal processing, improved receiver design, voice compression, and more efficient modulation schemes.

Multiple-access allocation schemes allow one to accommodate more than one user over a single RF channel by using either frequency-division multiple access (FDMA), time-division multiple access (TDMA), and code-division multiple access (CDMA). High-capacity radio systems require some sort of protecting receivers from interfering transmitters operating in the same frequency region. With analog FDMA, this is achieved through bandpass filters. Alternatively, TDMA provides time-slot separation, while CDMA assigns spread spectrum codes to separate information signals over wide-band channels.

Frequency-division multiple access (FDMA) is a widely used approach for analog cellular communications such as the advanced mobile phone system (AMPS), in which each call is assigned two 30 kHz narrow-band frequency-division duplex (FDD) channels. Typically TDMA is used in conjunction with FDMA, each RF carrier supporting multiple TDMA time slots for different users.

Within the general class of spread spectrum technology there are two major approaches: direct-sequence–code-division multiple access (DS-CDMA) and frequency-hopping multiple access (FHMA). Frequency hopping alternates carrier frequencies in accordance to a pseudorandom pattern. Implementation of such codes at the receiver allows each sender's signal to be recovered. Multiple transmitters using FHMA patterns would eventually interfere unless synchronized. In direct-sequence CDMA, each bit of the user's digital signal is spread by a higher-frequency chip sequence using unique orthogonal Walsh codes for each user.

North American Dual-Mode AMPS-TDMA

The North American dual-mode AMPS-TDMA standard (2,3) is a narrow-band mobile cellular system, in which one mode of operation is the AMPS, and the second mode of operation is the TDMA.

The dual-mode cell-site configuration is based on a programmable dual-mode radio and much supporting equipment is software controlled, offering both analog and digital services from the same cell site. The cell site is a multiple-access network, in which each channel is individually modulated by the respective radio, up-converted, amplified, and combined to form a high-power channel group. The composite RF signal is then fed to an antenna and transmitted. On the receive path, the incoming weak RF signal is amplified by a low-noise amplifier, split into several signals, and fed into the respective radio receivers for demodulation and signal recovery.

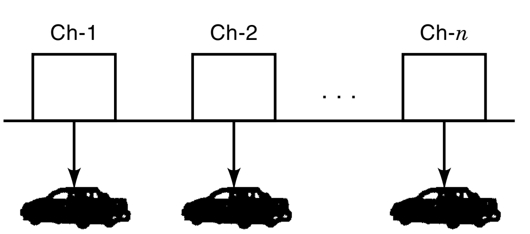

Figure 1. FDMA technique used in AMPS in which voice communication is based on FM and call set up is based on FSK.

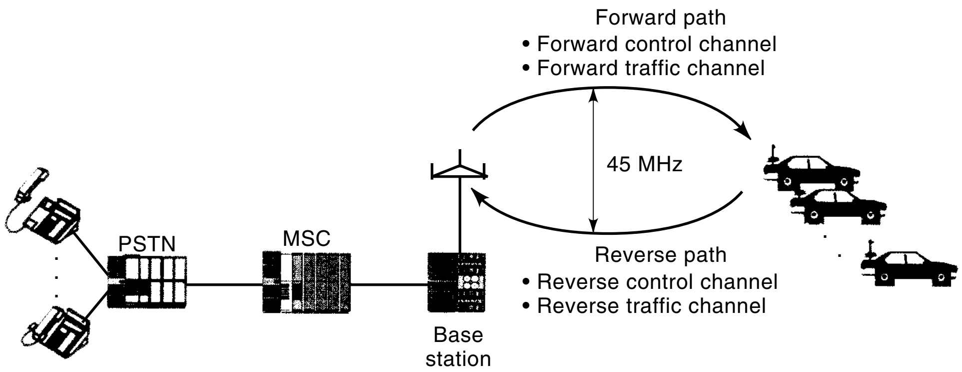

Figure 2. AMPS full duplex operational scheme.

An identical receive path provides space diversity, which receives the same signal through a separate antenna. The two receive signals are then compared and the strongest signal is selected; this is a built-in feature within the radio. The cell site is connected to the mobile switching center through a cross-point switch via a T_1 link. The cross-point switch also converts T_1 data from serial to parallel and parallel to serial format. Radio port assignments are performed during cell-site engineering.

Once the cell site is configured, the radio port assignment can be changed dynamically only in second-generation technologies that implement DCA. The entire communication process is controlled and monitored by the system intelligence, resident in the mobile switching center (MSC).

AMPS. The AMPS mode of operation is based on the FDMA technique (Fig. 1) in which each FDMA channel is used by a single mobile, via frequency-modulation (FM) transceivers. This is accomplished by dividing the 12.5 MHz band into 416 narrow-band FDMA channels, 30 kHz wide each.

Among them, 21 channels are used as control channels. The remaining ($416 - 21 = 395$) channels are used as voice channels. AMPS is a frequency-division duplex communication system (FDD) in which simultaneous transmission takes place in both directions, identified as (1) forward path or down link and (2) reverse path or up link, shown in Fig. 2. The forward path is comprised of two communication channels: (1) forward control channel and (2) forward voice channel. Similarly, the reverse path consists of two channels: (1) reverse control channel and (2) reverse voice channel. The control channels are used for channel assignment, paging, messaging, etc., and voice channels are used for conversations. A 45 MHz guard band is provided to avoid interference between forward and reverse channels as indicated in Fig. 2.

An additional radio known as the *locate receiver* is used in the base station to locate mobile units within a cell or a sector. This radio is used as a scanning receiver in which the transmitter is disabled. It is used to measure received signal strengths from certain mobile phones upon receiving a command from the MSC. The measured signal strengths are then used to determine a candidate cell for a possible call transfer (hand-off).

The communication between the base station and the mobile phone is based on a special call-processing protocol, described in the IS-54 standard (3). A brief description of this process is given in the following section.

AMPS Call Processing. There are 21 control channels and 395 voice channels in each band, in which the control channels are located between band A and band B as shown in Fig. 3. Control channels are used for channel assignment, paging, messaging, etc., and voice channels are used for conversations. Voice channels are also used intermittently for hand-off while the call is in progress.

The basic cellular call processing involves

1. Land to mobile call
2. Mobile to land call
3. Mobile to mobile call
4. Hand-off

These call processing functions are presented in the following.

AMPS Voice Channel. The AMPS voice channel is composed of a forward voice channel (FOVCH) and a reverse voice channel (REVCH) over which voice and signaling transmission takes place between the base station and mobile unit (Fig. 4). The channel separation between FOVCH and REVCH is 45 MHz. There are 395 voice channels in band A and 395 voice channels in band B. All voice channels carry analog voice, signaling, and data information. It is important to note that voice and signaling takes place in the analog domain (FM) and data transmission takes place in the digital domain (FSK) during hand-off. During this period (~100 ms to 200 ms) the voice is muted and the channel becomes a digital channel (FSK modulation), similar to the control channel.

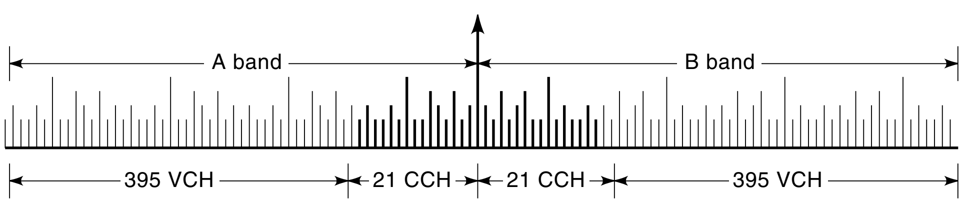

Figure 3. AMPS frequency spectrum showing relative position of the A band and B band along with respective control channels (CCH) and voice channels (VCH).

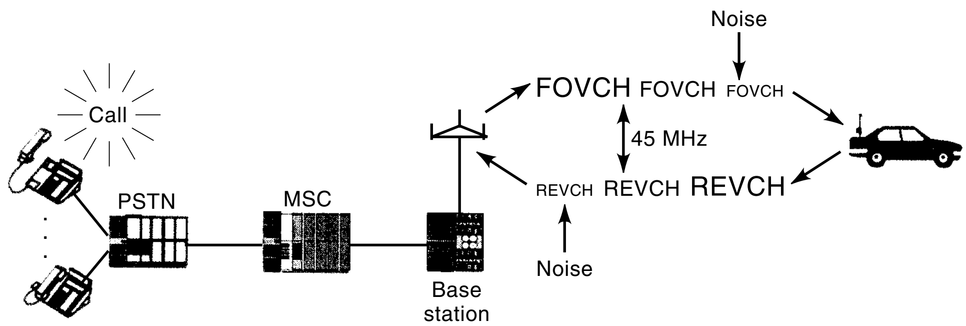

Figure 4. Symbolic representation of the voice channel, which is based on FM.

Each voice channel pair supports a single conversation at a time. Four different types of signals are transmitted over the voice channel during the course of a cellular call:

1. Voice signals
2. Supervisory audio tone (SAT)
3. Signaling tone (ST)
4. Data

SAT and ST tones are embedded into the voice (multitone FM). The voice signal is muted during hand-off and becomes a FSK-modulated channel for approximately 200 ms for hand-off completion. A brief description of these signals along with the method of transmission follows.

AMPS Voice Signal Transmission. On the transmit side, the voice signals are first compressed by a 2 : 1 syllabic compressor and then modulated by an FM modulator with ±12 kHz frequency deviation. On the receive side, the incoming signal is demodulated and decompressed as 1 : 2 to recover the voice. The compression and decompression techniques are based on simple preemphasis and deemphasis circuits (low-pass–high-pass filters). This process improves the noise performance of FM transmission.

Adjacent Channel Interference. Although FM side bands are mostly filtered out, a small fraction of side-band energy still remains due to nonideal filtering. As a result, adjacent channel interference occurs due to energy slipover between two adjacent channels, as illustrated in Fig. 5. This is a primary cause of adjacent channel interference in AMPS, which can be predicted by means of the following formula:

$$C/I = 10\log[(d_c/d_i)^{-g} + \text{(attenuation by the radio)} \quad \text{(26 dB EIA Standard)} \tag{1}$$

where C is the carrier, I is the interference, d_c is the distance between the serving base station and mobile phone, d_i is the distance between the interfering base station and mobile phone, and g is a direct representation of the propagation medium and will be influenced primarily by the degree of clutter found in urban, suburban, and rural environments. C/I will also depend on the propagation medium. It is measured in decibels. Table 1 represents typical ranges and subscriber densities used to define rural, suburban, and urban scenarios. With $g = 2$ (free space), $g \sim 2.5$ (rural), $g \sim 3$ (suburban), $g \sim 4$ (urban), we obtain a set of curves as shown in Fig. 6 as a function of C/I, where the interferer distance is assumed to be d_i and the carrier distance is assumed to be d_c.

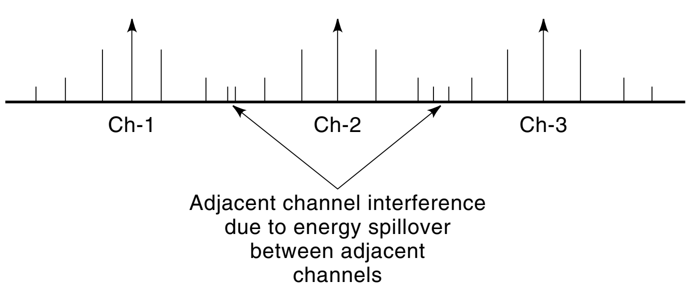

Figure 5. Adjacent channel interference due to energy spillover between adjacent channels.

Co-Channel Interference. A co-channel interferer has the same frequency as the desired signal. Co-channel interference arises due to multiple use of the same frequency as shown in Fig. 7. Thus, if the desired signal is defined as C and the interferer signal is defined as I, the C/I ratio will be given by

$$\begin{aligned} C/I(\text{dB}) &= 10\log[(1/N)(d_c/d_i)^{-g}] \\ &= 10\log[(1/N)(d_i/d_c)^{g}] \end{aligned} \tag{2}$$

where g is the pathloss slope and N is the number of interferers.

Thus, C/I depends on the propagation factor g.

Data Transmission Over the Voice Channel. During hand-off, the frequency-modulated voice channel momentarily becomes a FSK-modulated digital channel, similar to a control channel. A 10 kbit/s data transmission takes place between the base and the mobile stations for channel assignment and signaling. Voice, SAT, and ST tones are muted during this process. Once the channel assignment is complete, regular conversation resumes. About 200 ms worth of voice is muted during this process, which may be heard as a click noise during a conversation.

Cellular Control Channel. The cellular control channel is composed of a forward control channel (FOCC) and a reverse control channel (RECC) over which data transmission takes place between the base station and mobile unit. The channel

Table 1. Typical Subscriber Scenarios

Area \ Variable	Subscriber Density (subscribers/km^2)	Local Loop Distance (km)
Remote	0.01–0.1	>10–20
Rural	0.1–5	>3–5
Suburban	1–100	1–5
Urban	>100	<2–3

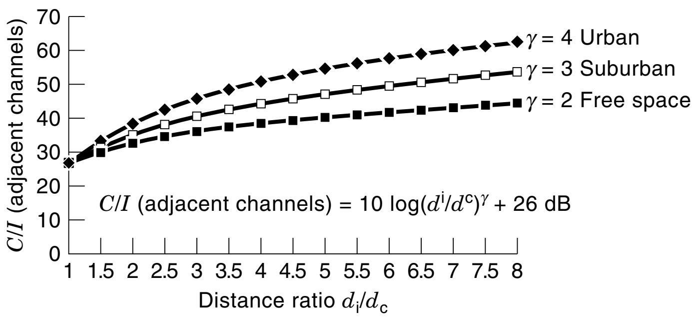

Figure 6. Adjacent channel interference as a function of distance ratio in different propagation media.

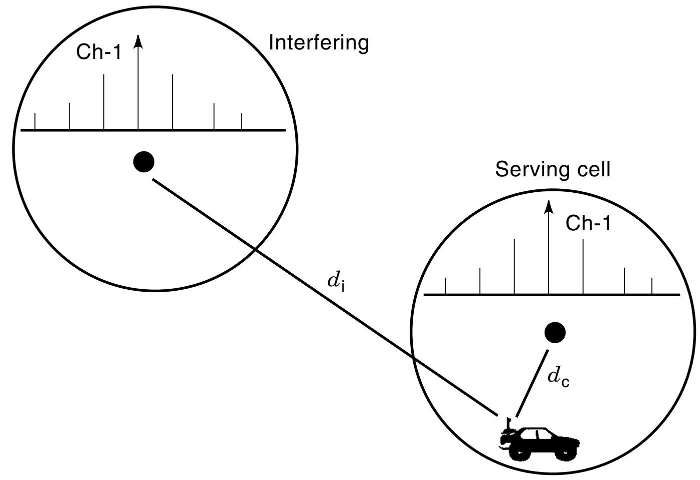

Figure 7. Co-channel interference due to frequency reuse.

separation between FOCC and RECC is 45 MHz. Control channels, used to set up calls, are also known as setup channels. There are 21 control channels in band A and 21 control channels in band B. The FOCC is transmitted from base station to mobile for paging, channel assignment, overhead, etc. The RECC is transmitted by the mobile to base station to originate a call. A control channels carry data information that is transmitted by means of FSK modulation with ±8 kHz frequency deviation. The channel is protected by BCH code. In the forward path, the impaired data are monitored, detected, and corrected by the mobile receiver. In the reverse path, the impaired data are monitored, detected, and corrected by the base-station receiver.

Data Transmission Over RECC. Control data are transmitted over the RECC. This channel is also known as the *access* channel and is used by a mobile transmitter to access a landline or a mobile telephone (Fig. 8). It begins with 48 synchronized bits for bit synchronization followed by five 48 bit words (A, B, C, D, E), each repeated 5 times for redundancy. Data transmission over RECC is based on a continuous wide-band 10 kbit/s data stream sent from a mobile transmitter to a base station, encoding 36 control bits into a (48,36,5) BCH code. This means that if the decoded word encounters more than two errors due to noise, interference, fading, an alarm will be generated and the word will be declared invalid, thus reducing the RECC capacity. Both FOCC and RECC channels are full duplex and operate in a coordinated manner. The objective of this section is to examine the control channel while operating in the presence of interference and Rayleigh fading and determine its call-handling capacity.

RECC Capacity. Control-channel capacity is a major concern in cellular communication since there is only one control channel per sector and three control channels per cell. Therefore it is desirable to identify the factors that limit the capacity (4).

In order to proceed with this exercise, let us consider the system model shown in Fig. 9, where noise is introduced in both forward and reverse control channels. The channel is partitioned into two functional blocks: RF and base band. It is assumed that the decision mechanism is resident into the base band in which the incoming impaired data through the RECC are processed. The outgoing data through FOCC are also impaired by noise, interference, and fading; they are processed by the mobile receiver and will not be considered in this analysis. It is further assumed that the FOCC performance is degraded by data impairments in the RECC since both channels work in a coordinated manner.

Assuming that the decision is taken by detection of three correct words out of five in any order, we obtain

$$P_d = \sum_{i=0}^{2} \binom{5}{i} \mathrm{WER}^i (1-\mathrm{WER})^{5-i} \tag{3}$$

where P_d is the probability of correct detection of three words out of five and WER is the word error rate.

There are 48 bits per encoded word and each word detects two errors (EIA Standard). Therefore the WER will be given by

$$\mathrm{WER} = \sum_{j=2+1}^{N} \binom{N}{j} \mathrm{BER}^j (1-\mathrm{BER})^{N-j} \tag{4}$$

where $N = 48, j = 3, 4, \ldots, 48$, and BER is the bit error rate.

Being a cellular radio channel, the BER depends on C/I and Rayleigh fading. This can be computed as (5,6):

$$\mathrm{BER} \approx \frac{1}{2 + C/I} \qquad \text{(thermal noise neglected)} \tag{5}$$

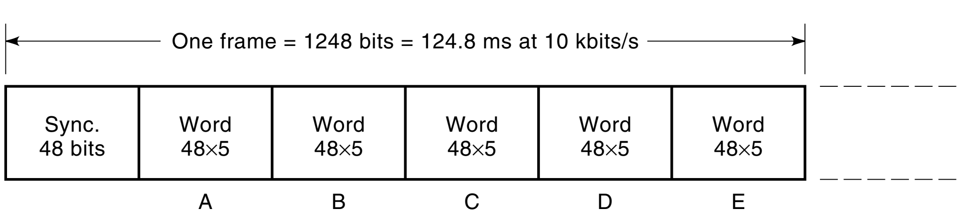

Figure 8. Reverse control channel.

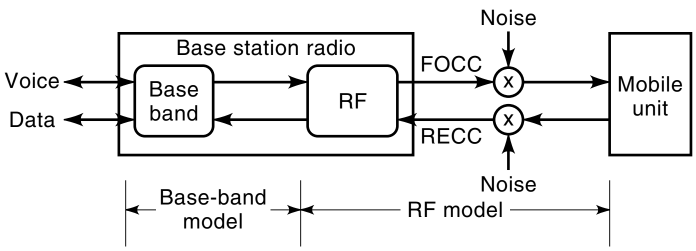

Figure 9. Control channel evaluation model.

where

$$C/I \approx \frac{1}{N-1}\left(\frac{D}{R}\right)^{\gamma} \qquad (6)$$
$$D/R = \sqrt{3N}$$

and where R is the radius of the cell, D is the repeat distance, N is the frequency plan (N = 4, 7, 9, . . .), and g is the propagation constant (g = 2 in free space, $g > 2$ elsewhere). According to EIA specifications, the busy/idle bit must remain busy for at least 30 ms after the reception of the last word from the mobile transmitter. This is to accommodate false detection of words due to interference and fading. If a mobile transmitter cannot complete the call within the RECC frame time T_R + 30 ms, the mobile transmitter is given additional time to complete the call. This process involves a serial search algorithm that continues until the correct word is obtained. The average elapsed time to reach a good agreement is given by

$$\begin{aligned} T_{acq} &= (T_R + \Delta t) + [\Delta t(P_F) + 2\Delta t(P_F)^2 + \cdots] \\ &= (T_R + \Delta t) + \Delta t(P_F) - n(P_F)^{n-1} \\ &= T_R + (\Delta t + \Delta t(P_F)/(1 - P_F)^2, \quad n = 1 \end{aligned} \qquad (7)$$

where T_{acq} is the average acquisition time, T_R is the RECC frame time in ms, Δt is the 30 ms, and P_F is the false detection probability.

The term $\Delta t + \Delta t(P_F)/(1 - P_F)^2$ is the BIS delay, which is a function of C/I and Rayleigh fading. The effective capacity then becomes (4):

$$\text{Capacity} = \frac{1}{T_{acq}} = \frac{1}{T_R + \Delta t + \Delta t(1 - P_d)/P_d^2} \qquad (8)$$

where $P_d = 1 - P_F$ is the correct detection probability, $\Delta t + \Delta t(1 - P_d)/P_d^2$ is the BIS delay, T_R = 124.8 ms (constant), and Δt = 30 ms (minimum).

Equation (6) is plotted in Fig. 10 as a function of C/I, which shows that the capacity is insensitive to C/I for $C/I > 14$ dB; this is due to error control coding. The capacity degrades

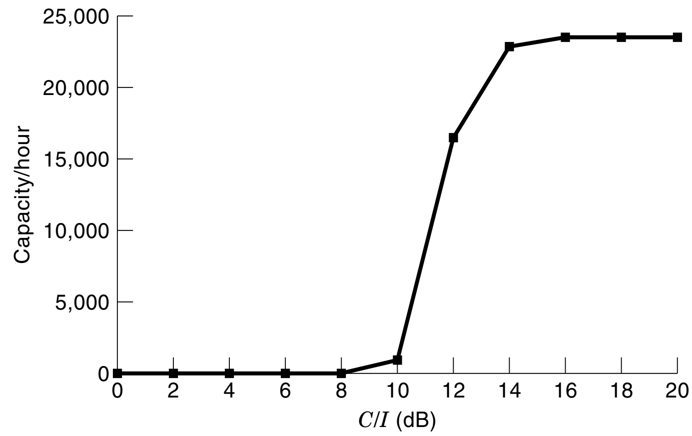

Figure 10. RECC capacity as a function of C/I.

slowly for 12 dB < C/I < 14 dB and degrades rapidly for C/I < 12 dB. In the absence of interference, $P_d = 1$ and the capacity becomes 23,256 per hour at a BIS delay of 30 ms and 11,880 per hour at a BIS delay of 175 ms.

FOCC. The FOCC (Fig. 11) is a continuous 10 kbit/s data stream sent from the base station to the mobile receiver. It begins with a 10 bit synchronous word for bit synchronization followed by a 11 bit synchronous word for frame synchronization. Following the synchronous word are *three* unique information streams:

1. Stream A is minimum if LSB = 0
2. Stream B is minimum if LSB = 1
3. Busy/idle stream (BIS); busy = 0, idle = 1

The BIS bit is embedded into the A-B data stream (one busy or idle bit every 10 data bits). It indicates whether the RECC is occupied or not. The frame length is 42.1 ms when the BIS bit repeats at 1 kbit/s.

FOCC Paging Capacity. The paging is interrupted during channel assignment (4); once every T_{acq}. Thus, page interruptions due to channel assignment will be given by

$$\text{Page interruptions} = T_F/T_{acq} \qquad (9)$$

where T_F = 42.1 ms, $T_{acq} = T_R$ + BIS delay, and T_R = 124.8 ms. With BIS delay = 30 ms (minimum), 175 ms (maximum); the page interruption due to channel assignment will vary between 14% and 27% of the time. According to the EIA Standard, the overhead messages repeats every 0.8 s. This translates into a page interruption approximately 5% of the time. The combined page interruption, therefore, varies between 19% and 32% of the time. Thus the FOCC will be occupied by paging between 81% and 62% of the time.

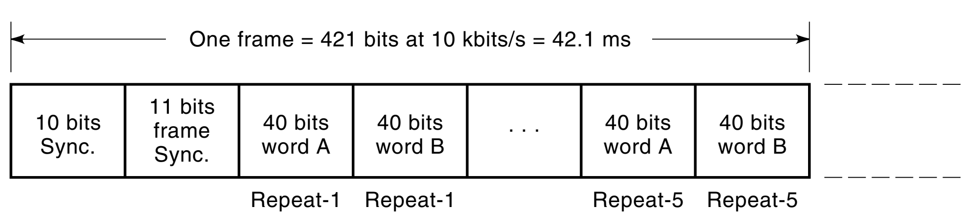

Figure 11. Forward control channel.

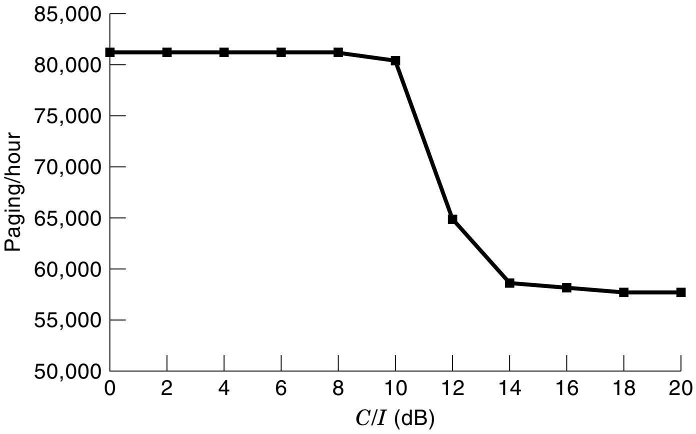

Figure 12. FOCC paging capacity as a function of C/I.

The capacity can be expressed as

$$\text{Number of page originations} = \frac{1}{T_\text{F}}(1 - T_\text{F}/T_\text{acq}) \tag{10}$$

where $1 - T_\text{F}/T_\text{acq}$ is the page occupancy time, $T_\text{acq} = T_\text{R} + \Delta t + \Delta t(1 - P_\text{d})/P_\text{d}^2$, P_d is the detection probability, which is a function of C/I. Equation (10) is plotted in Fig. 12 as function of C/I. For $C/I < 10$ dB, the RECC is overcome by interference, no channel assignment takes place, and page interruption is zero; hence the number of page originations is at maximum. As C/I increases, the RECC channel opens, the rate of channel assignments increases, and page interruption increases, thus reducing the paging capacity. Therefore the performance of FOCC is inversely proportional to the performance of RECC.

North American TDMA

The North American TDMA (IS-54) (3) is a narrow-band (30 kHz) mobile cellular system, which supports dual-mode (AMPS-TDMA) as well as analog-only mobile systems. Since the transmission bandwidth is only 30 kHz, the digitized 64 kbit/s voice data are first compressed by means of a vocoder, encoded for error control coding, modulated, and finally transmitted over the air as depicted in Fig. 13.

On the transmit side, the voice is first digitized and then compressed by means of a vocoder to form a low-bit-rate data stream. The compressed data are then encoded by means of rate 1/2 convolutional encoder and interleaved. Together with frame overhead, the composite bit rate becomes 16.2 kbit/s for each user. This 16.2 kbit/s data are distributed among two 6.66 ms time slots, 8.1 kbit/s data per time. Three of these 16.2 kbit/s subscriber data are combined to form a 48.6 kbit/s TDMA frame.

In the forward link, the base station modulates the composite 48.6 kbit/s data stream by means of a one fourth DQPSK modulator for transmission. In the reverse link, the mobile modulates the 16.2 kbit/s data by means of a one fourth DQPSK modulator for transmission. In the receive side, the data are recovered by means of a reverse process as shown in Fig. 13.

In the next section, we examine the underlying principle of communication of the digital cellular system.

Multiple Access Techniques in TDMA. The North American TDMA is a hybrid process in which each FDMA channel is time-shared by six mobile systems (presently three mobile systems) to accomplish TDMA, as shown in Fig. 14. It implies that when one mobile system has access to the channel, the other two are idle. This is achieved by means of a special frame structure, which is yet to be discussed. The TDMA channel capacity is therefore three times the FDMA in TDMA-3 and six times the FDMA in TDMA-6.

The TDMA has several advantages over the AMPS:

- Increased channel capacity
- Greater immunity to noise and interference
- Secure communication
- More flexibility and control

Moreover, it allows the existing AMPS standard to coexist in the same TDMA platform, sharing the same RF spectrum.

North American DS-CDMA Standard

The North American DS-CDMA standard (IS-95) (7) is a dual-mode wide-band spread spectrum cellular system, in which one mode of operation is the AMPS and the other model of operation is the CDMA. The CDMA standard is the subject of discussions in this section.

Introduction to CDMA. CDMA is a spread spectrum (SS)–based multiple-access radio communication system in which multiple users have access to the same frequency band. Here, *spectrum* refers to power spectrum associated with the base band signal. *Spread spectrum* refers to the spreading and despreading of binary data by direct application of a high-speed pseudorandom noise code over a given transmission bandwidth. This high-speed spreading rate is known as the chip rate. The overall process is described as the direct sequence–code-division multiple access or simply DS-CDMA. In DS-CDMA the composite high-speed data are then modulated and transmited over the air.

In the North American DS-CDMA standard the rate of the PN sequence was chosen to be approximately 1.25 MHz (~1.228 MHz) and the transmission bandwidth was chosen to be exactly 1.25 MHz. Ten different frequency bands are derived from the existing 12.5 MHz cellular carrier (A or B). Each of these bands supports 64 orthogonal codes known as *Walsh codes,* one Walsh code per user.

Basic Concept of Spread Spectrum. Understanding of CDMA begins with the basic concept of spectrum and the process of spectrum spreading. This concept is briefly presented in the following.

Spectrum. We begin our review by considering a simple discrete time circuit as shown in Fig. 15(a), which is loaded by a resistor R and driven by a nonperiodic discrete time signal having the following boundary conditions:

$$V(t) = \begin{cases} V, & 0 < t < T \\ 0, & \text{elsewhere} \end{cases} \tag{11}$$

This signal is also known as nonreturn to zero (NRZ) data, generally used in digital radio. Now, our goal is to determine

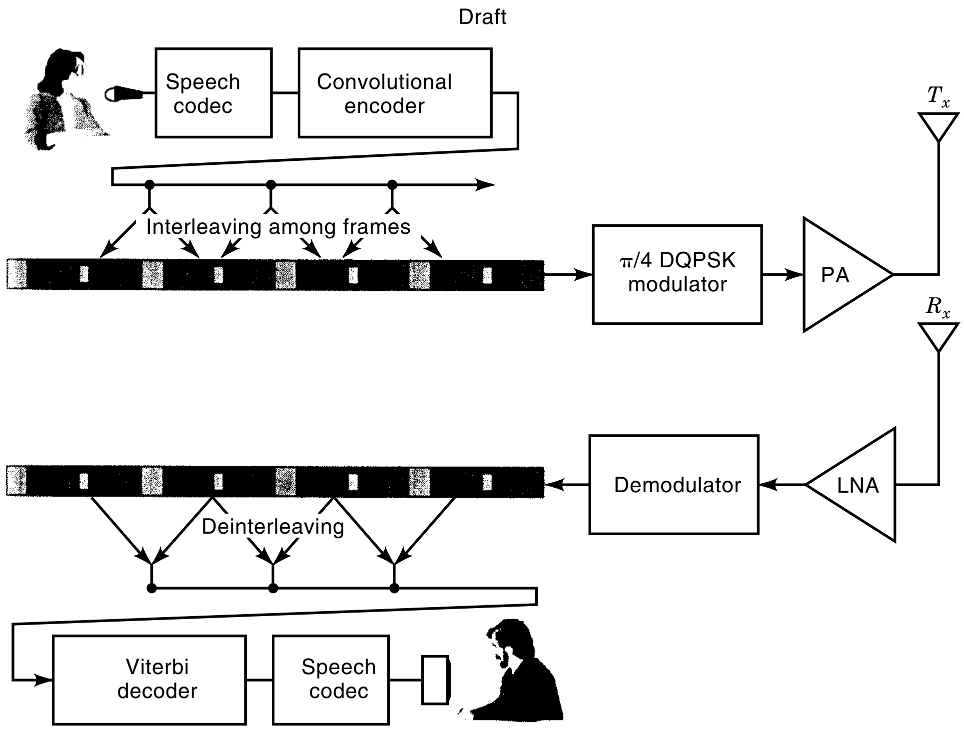

Figure 13. A simplified functional block diagram of the North American TDMA cellular radio.

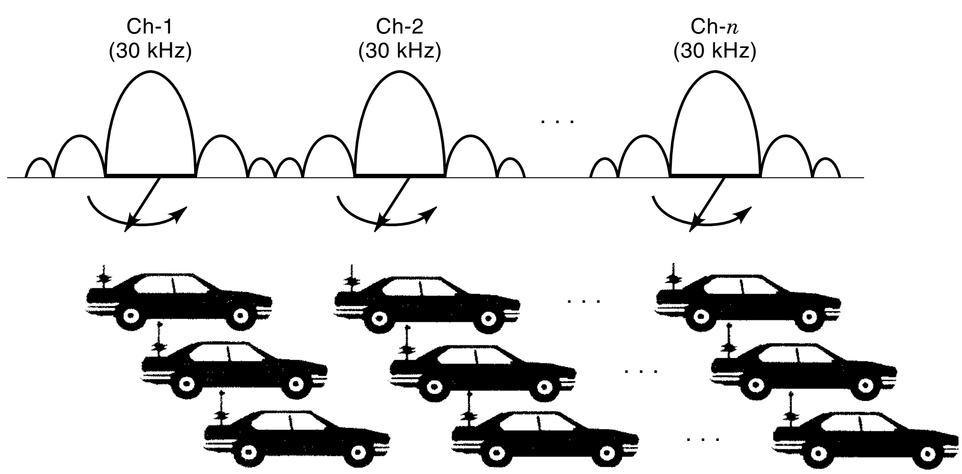

Figure 14. The North American TDMA-3 structure in which each AMPS channel is time-shared by three mobile phones to obtain TDMA-3.

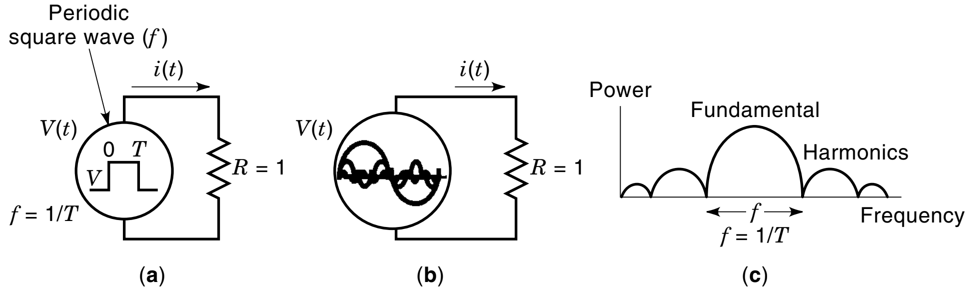

Figure 15. (a) A discrete time circuit; (b) equivalent circuit; (c) power spectrum.

the frequency content of this signal and then to evaluate the power spectrum associated with this signal.

To determine the frequency and power spectrum of the signal described in Eq. (1), we apply the Fourier transform:

$$\begin{aligned} S(\omega) &= \int_0^T Ve^{-j\omega t}\,dt \\ &= 2\frac{V}{\omega}\sin(\omega T/2) \\ &= VT\,\frac{\sin(\omega T/2)}{\omega T/2} \end{aligned} \tag{12}$$

which reveals that NRZ data are composed of an infinite number of harmonically related sinusoidal waves having different amplitudes as shown in Fig. 15(b). Therefore the power dissipated by the load resistance R will be due to all the sinusoidal components, which can be determined as

$$\begin{aligned} P(\omega) &= \frac{1}{T}|S(\omega)|^2 \\ &= V^2T\left(\frac{\sin(\omega T/2)}{\omega T/2}\right)^2 \end{aligned} \tag{13}$$

Fig. 15(c) shows the familiar power spectrum of a main lobe corresponding to the fundamental component of the frequency and an infinite number of side lobes corresponding to the harmonic components. We also note that most of the power is retained by the main lobe, the bandwidth of which is given by $1/T$, where T is the bit duration.

Spectrum Spreading. Spectrum spreading can be accomplished simply by increasing the frequency of the discrete time signal. Thus we consider a waveform with an amplitude V and frequency f ($f = 1/T$) and then increase the frequency of the same waveform by a factor of n, that is, T is now reduced by n. A pair of boundary conditions describing this situation is given in Eq. (14) and the corresponding waveform is shown in Fig. 16.

$$V(t) = \begin{cases} V, & 0 < t < T \\ 0, & \text{elsewhere} \end{cases}$$

and (14)

$$V(t) = \begin{cases} V, & 0 < t < T/n \\ 0, & \text{elsewhere} \end{cases}$$

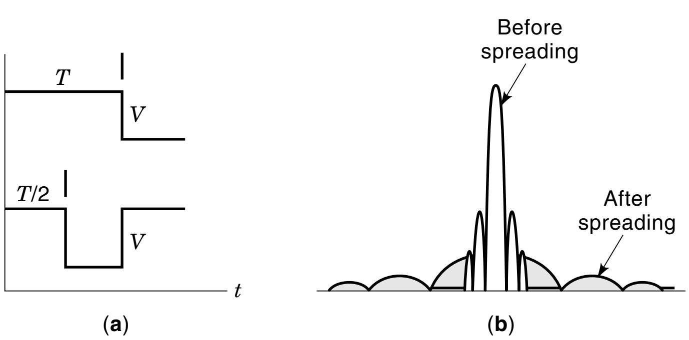

Figure 16. (a) Representation of a discrete time signal having an amplitude V and two different frequencies f and $2f$, $f = 1/T$. (b) The corresponding power spectrum.

Applying the Fourier transform in Eq. (14), we obtain the following spectral components. For $0 < t < T$:

$$\begin{aligned} S(\omega) &= \int_0^T Ve^{-j\omega t}\,dt = VT\,\frac{\sin(\omega T/2)}{\omega T/2} \\ P(\omega) &= \frac{1}{T}|S(\omega)|^2 = V^2T\left(\frac{\sin(\omega T/2)}{\omega T/2}\right)^2 \end{aligned} \tag{15}$$

For $0 < t < T/n$:

$$\begin{aligned} S(\omega) &= \int_0^T Ve^{-j\omega t}\,dt = VT\,\frac{\sin(\omega T/2n)}{\omega T/2n} \\ P(\omega) &= \frac{1}{T}|S(\omega)|^2 = V^2T\left(\frac{\sin(\omega T/2n)}{\omega T/2n}\right)^2 \end{aligned} \tag{16}$$

Figure 16(b) shows the power spectrum for $n = 1$ and $n = 2$.

We now turn our attention to the energy delivered to the load between time $t = 0$ and $t = T$. This is given by the total area under the curve [Figure 16(b)]:

$$E(t) = \int_0^T P(\omega)\,dt = \frac{1}{T}\int_0^T |S(\omega)|^2\,dt = \text{const} \tag{17}$$

which means that the total energy under the power spectrum curve remains the same after spreading.

Processing Gain. Processing gain is due to spectrum spreading, defined as

$$G_s = 10\log\left(\frac{\text{BW}}{R_\text{b}}\right) \tag{18}$$

where G_s is the process gain, BW is the transmission bandwidth, and R_b is the bit rate. Process gain is a measure of system immunity to noise, interference, fading, etc. For example, if BW = 30 kHz, R_b = 10 kHz, then G_s = 10 log(30/10) = 4.77 dB. Now if we increase the bandwidth to 1.25 MHz, the process gain would be G_s = 10 log(1,250,000/10) = 20.97 dB, indicating better margin for noise, interference, and fading. Process gain is also a measure of system capacity, as we shall see later.

DS Spread-Spectrum Modulation and Demodulation Techniques. *Spread-spectrum modulation* is a process of modulating the spread spectrum baseband signal by means of a suitable modulator. This is accomplished as a combination of a MOD2 adder (exclusive-OR gate) and a high-speed digital modulator as shown in Fig. 17. The speed of the modulator is determined by the pseudorandom noise (PN)code rate. In North American CDMA, the rate of the PN code is specified as 1.2288 Mbit/s. Therefore the information rate at the output of the MOD2 Adder is also at 1.2288 Mbit/s in which the NRZ data are imbedded. The output of the modulator is the modulated intermediate frequency (IF) signal.

Spread-spectrum demodulation is a reverse process, as shown in Fig. 17. The spread-spectrum IF signal is first demodulated to obtain the composite spread spectrum data. The composite data are then MOD2 added with the same PN code to recover the original NRZ data.

Reverse-Link DS-CDMA. As an illustration, we present a conceptual model of a reverse-link DS-CDMA system, providing access to k mobile phones: M_1, M_2, . . ., M_k, using the

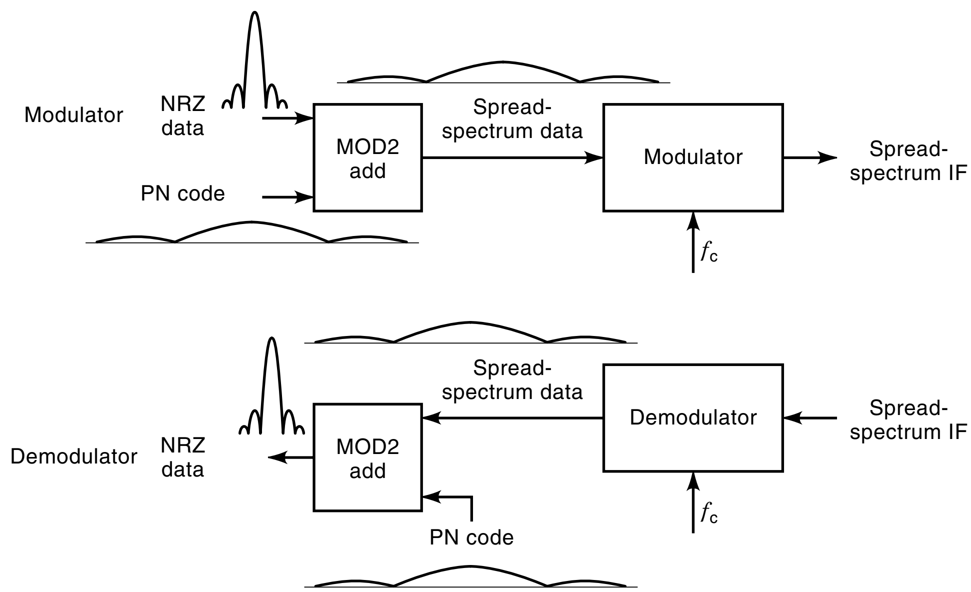

Figure 17. Spread-spectrum modulation and demodulation technique.

same carrier frequency f_c, shown in Fig. 18. Each mobile phone is assigned a unique PN code: PN_1, PN_2, . . ., PN_k, where PN_1 is assigned to M_1, PN_2 to M_2, and so on. The CDMA base station is assumed to be a multiple access point where all the propagated spread spectrum signals arrive at random. It is the responsibility of the base station to identify each traffic uniquely by means of an array of MOD2 adders, biased with the respective PN codes. Each MOD2 adder then despreads one of k signals that is the desired traffic.

Forward-Link DS-CDMA. The forward-link DS-CDMA process is described in Fig. 19. The incoming traffic from the T1 link is spread by means of an array of the MOD2 adder, biased with the respective PN codes (PN-1, PN-2, . . ., PN-k). Each spread-spectrum signal is then modulated up converted, and finally transmitted. These signals are received by all the mobile phones in the service area and are MOD2 added by the respective PN code to recover the desired traffic.

PN Sequence. This is accomplished by means of an m-bit generator that provides $2^m - 1$ different codes. The PN sequence is extensively used in digital communication systems for data scrambling due to its random properties. Out of these codes only m codes, known as orthogonal codes, are derived and assigned to m users, one code per user. The function of the PN code is to spread the traffic data over the entire transmission band while uniquely identifying each user. These random properties are generated by of a shift register having certain feedback. The total number of random sequences that can be generated by means of a m-bit shift register is given by

$$N = 2^m - 1 \tag{19}$$

These random sequences repeat themselves with the same random pattern. Although numerous PN sequences are available, only a few of them are used for cellular communication because of their unique correlation properties. These unique codes are known as *orthogonal* codes, having zero *cross-correlation* properties.

CDMA Frequency Bands. The existing 12.5 MHz cellular bands are used to derive ten different CDMA bands, 1.25 MHz per band, shown in Fig. 20. Each of these bands supports 64 Walsh codes, W0, W1, . . ., W63, where each code is designated as a channel. These codes are not permitted to be reused in the same band but can be reused in another band.

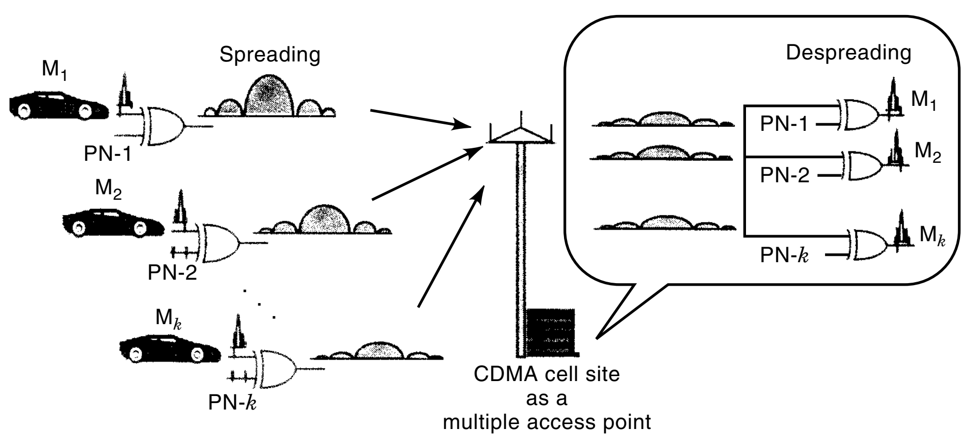

Figure 18. Conceptual representation of reverse-link DS-CDMA.

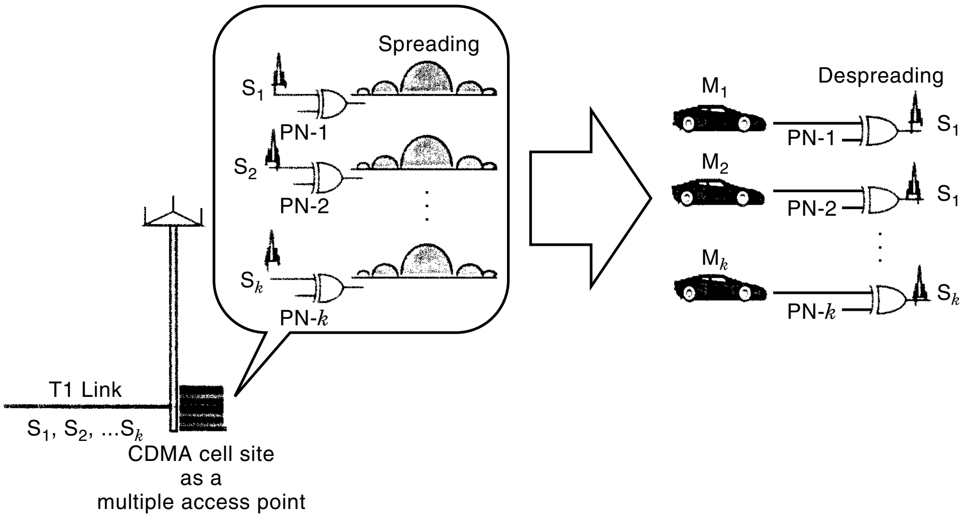

Figure 19. Conceptual representation of forward-link DS-CDMA.

On the other hand, several frequency bands are permitted to be used in the same cell or a sector for capacity enhancement, as long as the frequencies are different. This implies that both code planning and frequency planning are involved in CDMA.

CDMA Capacity. CDMA capacity can be classified into two categories: (1) soft capacity and (2) hard capacity. Soft capacity determines the maximum theoretical achievable capacity and the hard capacity is the practical capacity based on the number of Walsh codes and frequencies.

Soft Capacity. The CDMA soft capacity (N_s) is given by (8)

$$N_s = 1 + \frac{W/R_b}{E_b/N_0}\frac{F}{D}SH \tag{20}$$

where N_s is the number of simultaneous users per cell, W/R_b is the process gain, E_b/N_0 is the ratio of energy per bit to the noise spectral density, F is the frequency reuse factor (<1), D is the voice duty cycle (<1), S is the sectorization factor (3 for the tricellular plan), and H is the soft hand-off factor.

With W = 1.25 MHz, R_b = 9600 bit/s, D = 0.45, F = 0.64, S = 3, and H = 1.5 we obtain the soft capacity as a function of E_b/N_0, shown in Fig. 21. The total number of simultaneous users is maximized, depending on the minimum acceptable E_b/N_0. We find that two contradictory requirements exist for the capacity: (1) high capacity at the expense of E_b/N_0 and (2) high E_b/N_0 at the expense of capacity. It follows that a compromise is needed in which the capacity is high and the E_b/N_0 is minimum for which the BER performance acceptable.

Since all radios are based on some form of channel coding, we relate the coded bit error rate (BER_c) with the uncoded bit error rate (BER_u) as

$$\mathrm{BER_c} = m(\mathrm{BER_u})^n \tag{21}$$

where m and n are due to channel coding and the uncoded BER_u is due to the modulation scheme. For QPSK, this may be approximated as

$$\mathrm{BER_u} \approx \frac{\pi}{\sqrt{2}}e^{-E_b/N_0} \tag{22}$$

Combining Eqs. (19) to (21), we obtain (15)

$$N_s = 1 + nC\frac{G_s}{\ln\left(\dfrac{m\pi}{\sqrt{2}\mathrm{BER_c}}\right)} \tag{23}$$

which shows that the CDMA capacity also depends on modulation as well as on channel coding.

Figure 20. CDMA frequency bands.

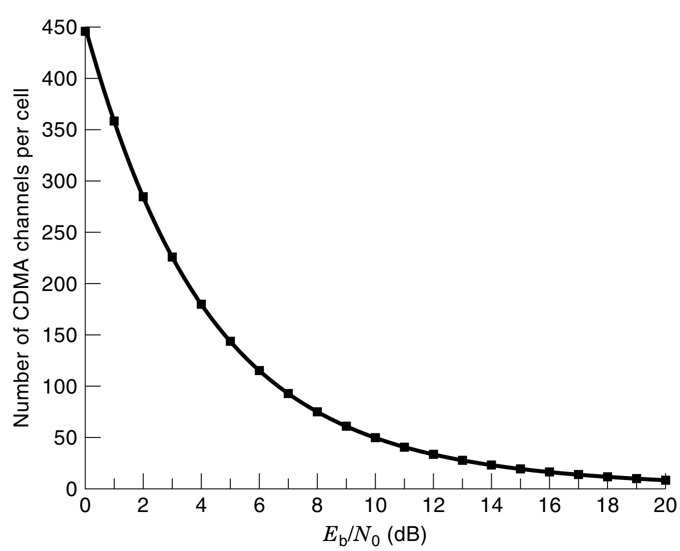

Figure 21. CDMA soft capacity as a function of E_b/N_0.

CDMA Hard Capacity. CDMA hard capacity is directly related to the number of Walsh codes and the number of frequency bands available to the system. It has also been claimed (4) that the same frequency band can be reused in every cell, allowing all the available frequencies to be used in the same cell. Then the hard capacity (N_h) can be evaluated as

$$N_h = (\text{Number of traffic Walsh Codes}) \times (\text{Number of Frequencies used}) \tag{24}$$

CDMA Power Control. In the operation of a direct-sequence CDMA system, adaptive transmitter power control (TPC) is required to maintain the received power from mobile units at comparable levels at the base station. In the preceding section, the CDMA soft capacity was established as

$$N = C\frac{G_s}{E_b/N_0} \tag{25}$$

where C is a constant that depends on the voice activity factor, sectorization, frequency reuse factor, and soft hand-off factor. The numerator G_s is the process gain, which is the ratio of the bandwidth to the bit rate (W/R_b). The denominator E_b/N_0 is related to the BER performance. For a given design parameters C and G_s, the capacity is then directly controlled by E_b/N_0, which is a function of the mobile transmit power.

Since it is desirable to maximize the capacity, the transmit power of each mobile has to be controlled so that its received power at the cell site is minimum irrespective of the distance. Therefore the objective of the mobile power control is to produce a nominal received power from all mobile phones in a given cell or a sector.

In the IS-95 Standard CDMA, power control is a three-step process:

1. Reverse-link open-loop power control (coarse)
2. Reverse-link closed-loop power control (fine)
3. Forward-link power control

The Near–Far Problem. Without TPC, the stronger signal from a mobile unit near the base station would override signals from more distant mobile units receiving weaker signals. This phenomenon is known as the near–far problem (9).

The near–far problem is illustrated in Fig. 22 for the case of two competing operators. In this example, the mobile unit at d_n is a customer of operator B, while the mobile unit d_d is registered with oprator A. Since both are at comparable distances from their home base stations, they each transmit at a comparable power levels. However, the unit at d_n is much closer to base station A and will have a power advantage over the mobile unit d_d of $(d_d/d_n)^g$, where g is an exponent determined by the propagation model (10). For example if $d_d = 200$ m and $d_n = 20$ m, we obtain the following ratio of distances:

$$d_d/d_n = 200\,\text{m}/20\,\text{m} = 10$$

Under free-space propagation, the exponent $g = 2$. Empirical mobile radio propagation models for urban and rural environments are described in the literature (11,12). If we assume

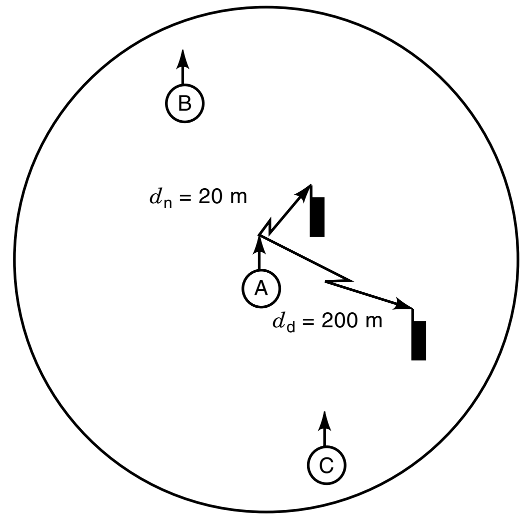

Figure 22. Near–far interference effect.

a fourth-order attenuation coefficient ($g = 4$) for urban environments. The ratio of received powers is equivalent to 40 dB, enough to swamp the exposed receiver.

$$10^g = 10^4 = 10,000 \qquad 10\log(d_d/d_n) = 40\,\text{dB}$$

Cell-site collocation helps to alleviate the near–far problem; however, it also restricts competition, forcing operators to keep the same pattern of base stations. The near–far problem is not exclusive to CDMA. Recent studies (13) recommend a certain level of collocation among cell sites of systems utilizing diverse PCS technologies, mainly at the fringes of contiguous band allocations.

Frequency-Hopping CDMA Techniques

Frequency hopping can offer better protection against the near–far problem than DS-CDMA, given the advantage of enabling the transmitter to change the carrier frequency and avoid in-band interfering signals. Near–far interference problems are dealt with by achieving frequency separation through hopping sequences.

Basic Concept. The classical frequency hopping is a spread-spectrum method in which each user is assigned a unique carrier frequency for a certain duration time (Δt). A hopping mechanism is built into the transmitter [Fig. 23(a)] to change the carrier frequency over a given band periodically. At the end of Δt, the radio assumes a new frequency in such a way that the same frequency is not used by another transmitter at the same time.

Method of Channel Hopping. The mechanism of channel hopping (1) is based on n fixed tuned radios and combiners in which the channels are controlled by an intelligent multiplexer/demultiplexer (IMD). In this method, each data stream is channelized by means of the IMD, driven by a PN code. The length of the PN code is determined by n, where n is the number of voice channels. This is accomplished by means of a m bit PN generator that provides of a set of $2^m - 1$ different codes. Out of these codes only m codes, known

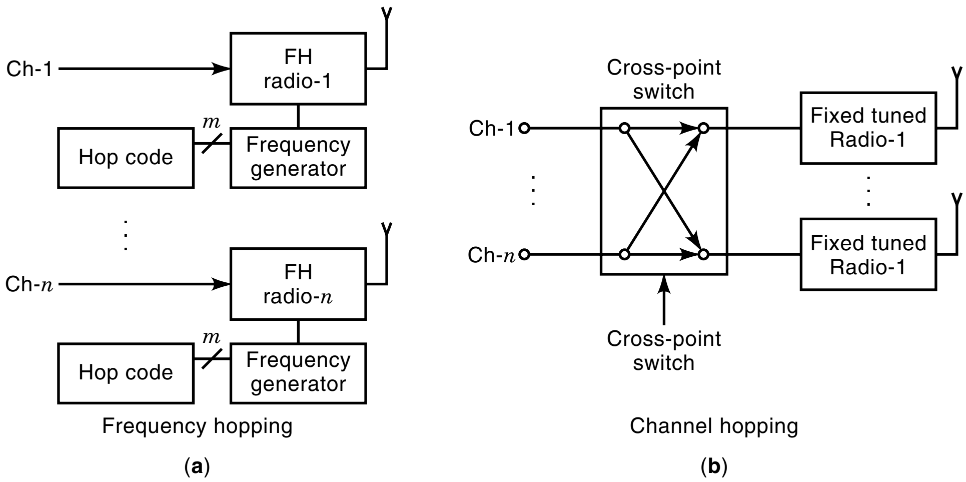

Figure 23. (a) The classical frequency-hopping radio in which the carrier frequency hops, and (b) the proposed frequency hopping based on channel hopping.

as orthogonal codes, are used to derive m different hopping frequencies. The hop rate is determined by $1/\Delta t$, Δt being the hop duration. On the receive side an identical PN generator synchronizes with the incoming bit stream in such a way that the receiver hops in step with the transmitter. As a result it is jamming resistant since the carrier frequency hops around at random. Frequency diversity is also an added advantage in this process. These advantages are at the expense of complexity and cost.

Use of Frequency Hopping. In frequency-hopping multiple access (FHMA), one can design a network based on n fixed tuned radios where the input channel hops rather than the carrier. This is accomplished by means of a cross-point switch driven by a hop code. Unlike classical frequency hopping, this hop code is *nonorthogonal,* and therefore simple to generate. The function of the cross-point switch is to deliver the modulating signal to each fixed tuned radio periodically, thus accomplishing the effect of frequency hopping. Consequently, nonhopping radios can be employed to accomplish a frequency-hopping multiple access network. It follows that today's FDMA and TDMA cellular networks can be transformed into frequency-hopping networks since cross-point switches are readily available. This method offers greatly simplified and cost-effective frequency hopping cellular services, eliminating the need for space diversity and costly replacements of cell-site radios.

With frequency hopping interference still appears in the event of a collision, and capacity limitations depend on how fast the synthesizer can change frequencies. Faster numerically controlled oscillators (NCOs) may eventually allow higher hopping rates, lower error rates, and greater capacity per unit of bandwidth. However, turning this device completely off between hops becomes increasingly difficult at higher switching speeds, involving additional concerns with regard to RF splatter. Synchronization at fast hopping rates becomes an issue as well. At the present time unless orthogonality and synchronization are incorporated, lower performance is expected for uncoordinated FHMA as compared to synchronous DS-CDMA systems.

Speech Compression Techniques

Speech Codec. Capacity in wireless systems can also be increased by elimination of redundancy through speech processing, which translates into lower data rates per channel and consequently a higher number of channels per MHz of spectrum. As an example, this section analyzes the speech-processing algorithm proposed in Standard IS-54 of a member of the code excited linear predictive coding (CELP) family known as vector sum excited linear predictive coding (VSELP).

The VSELP encoder is based on a 20 ms speech frame that is further divided into a series of four 5 ms subframes. Each 20 ms speech segment is encoded into a series of parameters in which each parameter represents a certain number of bits to form 159 bits per frame or 159/20 ms = 7950 bits/s (~8 kbit/s); this is the coded speech. The speech parameters and the associated bit representations are as follows.

For each 20 ms speech frame, the coder estimates two parameters: (1) average speech power, which is represented by a 5 bit word/frame and designated as $R(0)$, (2) short-term prediction filter coefficient represented by a 38 bit word/frame, designated as a_i, which has ten coefficients for the short-term prediction filter. These two parameters/frame represents a total of 5 + 38 = 43 coded bits/frame. The remaining 159 − 43 = 116 coded bits are represented by four subframes as follows.

For each 5 ms subframe, the speech coder estimates four parameters: (1) coded vector–1, represented by a 7 bit word/subframe, designated as I, (2) coded vector–2, represented by a 7 bit word/subframe, designated as H, (3) long-term prediction filter coefficient, represented by a 7 bit word/subframe, designated as "lag" or L, and (4) gains b, g_1, g_2; these coefficients are represented by an 8 bit word/subframe. These four parameters/subframe represent $(7 + 7 + 7 + 8) \times 4 = 116$ coded bits/frame. The total number of bits that represents a 20 ms segment of speech is therefore 43 + 116 = 159 coded bits per 29 ms or 7950 coded bits/s.

On the decoder side, these speech parameters are used to reconstruct the original speech. This is briefly described by means of Fig. 24. The VSELP decoder utilizes two VSELP excitation code books, code book–1 and code bood–2. These code books are tables of numeric values, represented as *excitation vectors* that are selected by the encoded parameters I and H, generated by the VSELP encoder. The output of the code books and the output of the long-term prediction filter are adjusted by the corresponding coefficients g_1, g_2, and b and

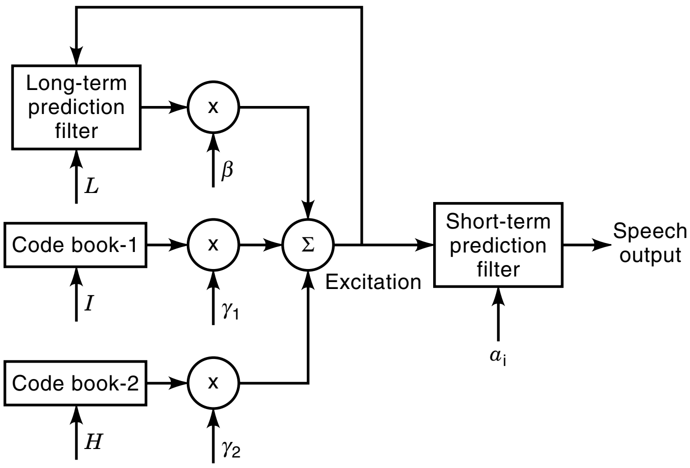

Figure 24. Block diagram of the speech decoder.

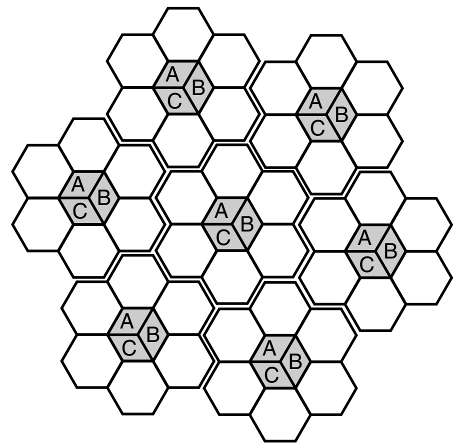

Figure 26. The classical $N = 7$ three-sectored plan $k \sim 3$.

then added to form an excitation for the short-term prediction filter the coefficients of which are those of a_i, generated by the encoder. The output of the short-term prediction filter is the desired decoded speech.

FREQUENCY REUSE

Radio signals experience multiple sources of degradation as they propagate, for example, white thermal noise, adjacent channel interference, and co-channel interference. The key determinant of system quality is the power of the desired signal as compared to undesired disturbances.

There are unavoidable tradeoffs between tight spatial reuse and bandwidth efficiency. Wireless systems are co-channel interfrence limited because of frequency-reuse considerations. Frequency planning optimizes spectrum usage, enhances channel capacity, and reduces interference. A frequency plan also ensures adequate reuse distance to an extent where co-channel interference is acceptable while maintaining a high channel capacity. In order to accomplish these diverse requirements, a compromise is generally made so that the target C/I (carrier to interference ratio) performance is acquired without jeopardizing the system capacity. A high

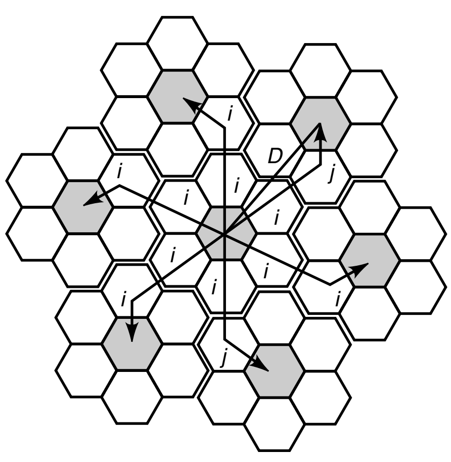

Figure 25. Illustration of the classical cluster reuse plan. $N = 7$ OMNI, $k = 6$.

grade of service depends on acceptable figures for the C/I. Network operators set a threshold of a minimum value of C/I that is acceptable to meet service quality objectives. However, the classical frequency planning techniques do not always permit this due to cluster reuse (14) as shown in Fig. 25. Here, all the co-channel interferers are equidistant from each other and the C/I is given by

$$\frac{C}{I} = 10 \log \left[\frac{1}{k} \left(\frac{D}{R} \right)^{\gamma} \right] \tag{26}$$

where $D/R = \sqrt{3N}$, D is the frequency-reuse distance, R is the cell radii, and $N = i^2 + ij + j^2$. i and j are known as shift parameters, 60° apart, and k is the total number of co-channel interferers. In general, $k = 6$ for OMNI plan and $k \sim 3$ for the three-sectored plan, illustrated in Fig. 25 and Fig. 26 respectively. From these illustrations we see that the classical $N = 7$ sectorized plan (Fig. 26) uses exactly the same frequency-reuse plan as OMNI (Fig. 25) without proper coordination with antenna directivity.

Consequently, a single D/R ratio determines C/I [see Eq. (26)]. Furthermore, there is a loss of Erlang capacity due to sectorization. Therefore, a mechanism is needed to coordinate antenna directivity and frequency reuse so that the number of dominant interferers is reduced and C/I is enhanced.

In this section, we present a method of directional frequency reuse (DFR) (15,16) that coordinates antenna directivity and yields an additional C/I margin and capacity. Unlike the conventional cluster reuse, the proposed method is based on group reuse in which C/I is redefined as a function of multiple reuse distances. As a result, the reuse distances can be traded for antenna downtilt and beam width to be more effective. These novel features are briefly presented in this section.

Conceptual Development

Unlike the classical definition [see Eq. (1)], we redefine C/I as a function of multiple D/R ratios:

$$\frac{C}{I} = 10 \log \left(\frac{1}{\left(\frac{D_1}{R}\right)^{-\gamma} + \left(\frac{D_2}{R}\right)^{-\gamma} + \cdots \left(\frac{D_k}{R}\right)^{-\gamma}} \right) + \Delta \,\mathrm{dB} \tag{27}$$

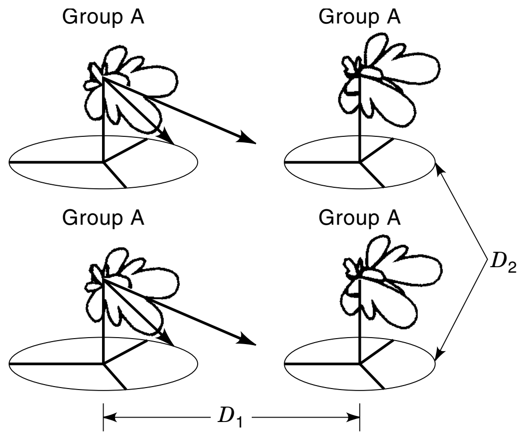

Figure 27. Illustrations of antenna directivity and multiple reuse distances.

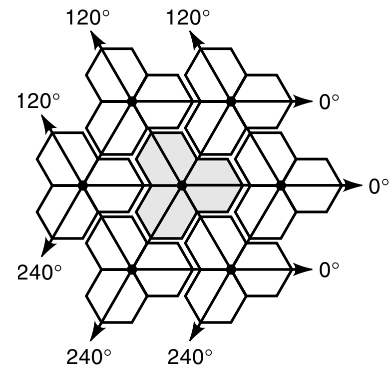

Figure 29. Principle of directional frequency reuse in a cluster of tricellular plan.

where D_1/R, D_2/R, . . ., D_k/R are reuse distances according to antenna directivity and Δ dB is an additional margin due to antenna downtilt, beamwidth, etc. This implies that, in a given propagation environment with a given antenna directivity, these reuse distances may be adjusted to acquire this extra margin (Δ dB). In other words, if antenna directivity permits, use a short reuse distance; otherwise, use a long reuse distance. This is illustrated in Fig. 27 for two antenna orientations.

As shown in Fig. 27, we have two reuse distances D_1 and D_2, where D_1 is associated with a pair of directional antennas, 180° out of phase, and D_2 is associated with a pair of directional antennas, 90° out of phase. This implies that a compromise may be reached between D_1 (180°) and D_2 (90°) for the respective downtilt and beam width to be more effective. The effective C/I then becomes

$$\left(\frac{C}{I}\right)_{\rm DFR} = 10\log\left(\frac{1}{(D_1/R)^{-\gamma} + (D_2/R)^{-\gamma}}\right) + \Delta\,\text{dB} \qquad (28)$$

This principle forms the basis of our development of the following directional frequency reuse (DFR) plan.

Principle of Directional Frequency Reuse

The proposed directional frequency-reuse plan is based on a tricellular platform, which is comprised of three identical cells (sectors), driven from a single source as shown in Fig. 28.

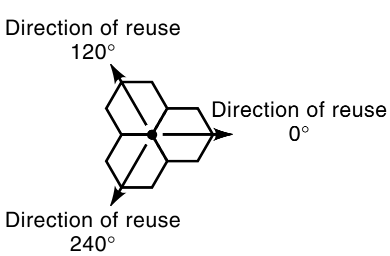

Figure 28. Principle of directional frequency reuse in a tricellular plan.

Since directional antennas are used in each cell, which are subsequently referred to as {*f*(0°)}, {*f*(120°)}, {*f*(240°)}, a group of frequencies is reused in one direction only. As a result, the worst-case co-channel interference is due to only one from the same direction. Expanding the principle, we obtain a seven tricellular pattern in which each of the three axes is comprised of three parallel layers, as shown in Fig. 29.

This directional frequency assignment results in a total of six or multiples of six frequency groups. Therefore, the available voice channels are divided up into six or multiples of six frequency groups, which are then distributed according to the principle just discussed, illustrated by means of $N = 6$ and $N = 4$ frequency plans in the following sections.

The $N = 6$ DFR

The $N = 6$ DFR is based on 18 frequency groups in which frequency groups are numbered as 1, 2, . . ., 18. These frequency groups are then directionalized and distributed alternately according to the following principle:

0°	120°	240°
1, 3, 5	7, 9, 11	13, 15, 17
2, 4, 6	8, 10, 12	14, 16, 18

A cluster of seven tricell groups, using this channel distribution pattern, is shown in Fig. 30. These reuse patterns are consistently used throughout the geographical service area.

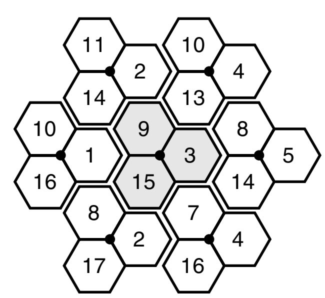

Figure 30. $N = 6$ directional frequency reuse.

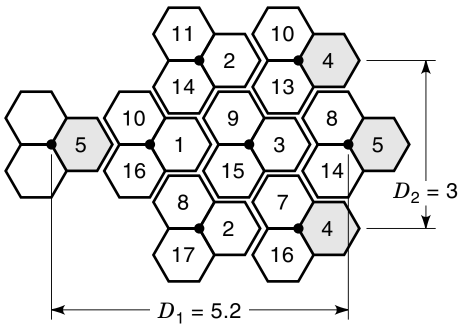

Figure 31. N = 6 directional frequency reuse growth plan.

The number in each sector represents the frequency group assigned to that sector. The growth plan, shown in Fig. 31, exhibits two different reuse distances $D_1/R = 5.2$ and $D_2/R = 3$. The effective C/I can be estimated as

$$\left(\frac{C}{I}\right)_{\mathrm{DFR}} = 10\log\left(\frac{1}{(5.2)^{-4} + (3)^{-4}}\right) + \Delta\,\mathrm{dB} \qquad (29)$$

where Δ dB depends on the antenna down tilt and beam width.

The N = 4 DFR

The N = 4 DFR is based on 12 frequency groups. These 12 channel groups are directionalized according to the following principle:

0°	120°	240°
1, 3	5, 7	9, 11
2, 4	6, 8	10, 12

Figure 32 shows the channel distribution within a seven tricellular platform. The corresponding C/I is

$$\begin{aligned}\left(\frac{C}{I}\right)_{\mathrm{DFR}} &= 10\log\left(\frac{1}{(3.46)^{-4} + (3)^{-4}}\right) + \Delta\,\mathrm{dB} \\ &= 17.1\,\mathrm{dB} + \Delta\,\mathrm{dB}\end{aligned} \qquad (30)$$

where Δ dB is a function of the antenna down tilt and beam width.

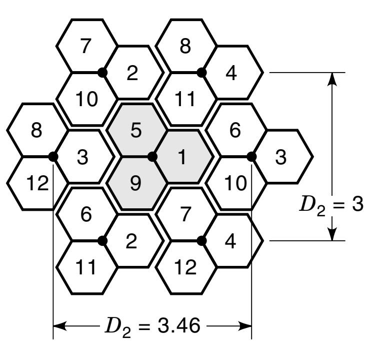

Figure 32. N = 4 directional frequency reuse.

CONCLUSIONS

We have presented a method of directional frequency reuse for high-density, high-capacity cellular networks. It is based on group reuse, instead of cluster reuse, yielding multiple reuse distances. Consequently, antenna down tilt and antenna beam width become more manageable, acquiring an additional C/I margin. Examples of N = 6 DFR and N = 4 DFR indicate that the principle of DFR is a viable high-capacity solution for cellular applications.

RADIO RESOURCE MANAGEMENT STRATEGIES

Channel assignment in radio systems can be fixed or dynamic. In a fixed channel assignment (FCA) system, available channels are reused in accordance to a repetitive pattern of channels grouping. The way these channels are grouped determines minimum acceptable quality levels to guarantee a desired C/I threshold. Traditionally a spectrum allocation process through fixed channel blocks implies economies of scale known as trunking inefficiencies. Alternatively channels can be allocated on demand to users from a common channel pool. This approach is known as dynamic channel assignment (DCA). Under DCA, channels must be assigned on demand according to co-channel interference levels. DCA allows capacity gains over FCA due to improved frequency reuse.

Besides capacity gains, an important advantage of DCA is its capability to improve resource management and avoid frequency planning for a wireless network (17,18). This access scheme also reduces efficiency losses arising from time-varying and nonhomogeneous traffic spatial distributions.

Trunking Inefficiencies with Fixed Channel Assignments

Spectrum blocks can be considered as traffic servers, and traffic theory states that a common group of channels will use the available spectrum more efficiently than if it is divided up among partitions (19). The efficiency losses of fragmenting the spectrum to allow utilization by multiple service providers can be expressed by the following formula (20):

$$h_{\mathrm{e}}(\%) = 100(A_1 - A_N)/A_1 \qquad (31)$$

where h_e is the efficiency loss in percent, A_1 is the traffic load served by a single operator with B channels, and A_N is the traffic load handled by N operators with B/N channels each.

Figure 33 illustrates spectrum efficiency losses against blocking probability, assuming equal traffic loads and the same quality of service (blocking probability) for N competing operators. We assume as well B = 832 available channels and a frequency-reuse pattern of N = 7. Traffic loads A_1 and A_2 are derived from the Erlang B model.

Dynamic Channel Assignment

System capacity in wireless networks can be improved by performing channel reassignment in the presence of outages. This can be achieved through implementation of escape mechanisms, such as dynamic channel assignment and interference-driven hand-offs. In our simulation we assumed single-channel FDMA Frequency Division Duplex (FDD) RF carriers

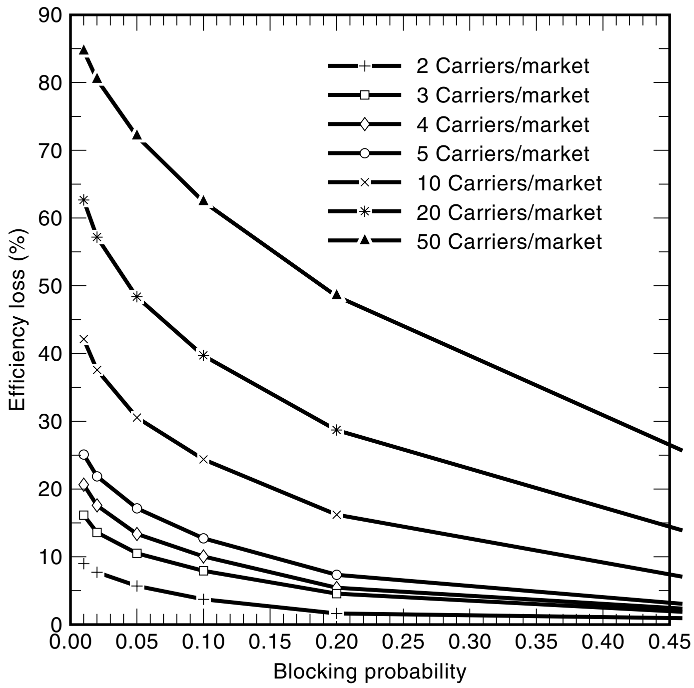

Figure 33. Trunking inefficiencies for multiple operators, with 832 channels. Block allocations case.

and a co-channel interference-limited system, so adjacent channel interference effects were neglected.

Advantages of Dynamic Channel Assignment. DCA has the potential to provide substantial capacity increases, mostly derived from the following spectrally efficient properties:

- *No Trunking Efficiency Losses.* Instead of subdividing the available spectrum into fixed groups, DCA allows the entire set of channels to be reused at any cell site.
- *Average Case Interference Scenario.* Fixed channel assignment (FCA) requires worst-case scenario considerations; DCA allows channel reuse ratios based on average co-channel interference. This improves margin requirements for log-normal shadow loss.
- *Adaptive Bandwidth Sharing.* In a dynamic multioperator environment, DCA allows a usage of channels that is proportional to each operator's market share.

Types of Dynamic Channel Assignment Strategies. Takenata et al. (21) have grouped channel assignment strategies into three categories:

- *Minimum reuse distance* strategies will not assign the same channel to any cell that is within a certain distance of a reference cell to which the same channel has already been assigned (22). This approach requires extensive communication among base stations.
- *Adaptive decentralized* strategies assign available channels relying on local information about signal levels and interference measured at the base station, handset, or both (23). Several algorithms can be used to select a channel that has an acceptable signal to interference level autonomously.
- *Optimization* strategies employ linear programming or neural networks to reconfigure the entire system each time a new channel assignment is made. The objective is to maximize a figure of merit such as an overall system *C*/*I*. Such methods are computationally intensive and require centralizing real-time *C*/*I* information that has been collected at each mobile unit and/or base station (24,25).

A particular kind of adaptive and decentralized DCA access scheme is called autonomous reuse partitioning (ARP) (26). ARP is a simple algorithm that allows for decision making directly at the cell sites and provides good performance without demanding centralized call assignment databases. ARP also provides an improved frequency reuse through cell sectorization into multiple concentric rings.

With ARP all base stations search channels in the same order and assign to the call the first channel that meets a minimum *C*/*I* threshold. Since users close to a base station are likely to achieve better *C*/*I* ratios, the first channels in the list are often assigned to calls originating near the base station; channels further down the list are assigned to calls originating near the cell boundary.

The benefits of DCA are bringing this feature into several wireless standards. As DCA can be utilized to provide autonomous frequency assignments, it is particularly suitable for microcell networks to ease frequency planning.

Open-Access DCA

Open-access or open-entry DCA is a spectrum-allocation scheme that presents several advantages over fixed bandwidth allocations, in particular economic efficiencies derived from market competition. Open-entry implies that a combination of electronics and market forces, rather than preset regulation, would determine the optimal number of competitive suppliers of wireless services. Market-based allocation mechanisms serve the public interest by encouraging lower service prices and improving service performance. To date open access could be achieved through mechanisms such as DCA.

Fixed block allocations lead to some inefficiencies in spectrum utilization: If multiple providers have unequal market shares, then those with smaller market shares are less efficient in using the assigned resource. Conversely, the operator with a larger market share may inefficiently invest in more base stations in order to increase frequency reuse and capacity. An open-access scheme would automatically adjust to changes in demand through an autonomous and decentralized architecture.

Also through regulation one could limit the number of operators sharing spectrum to no more than *N*, but open entry would permit the maximum sustainable levels of competition. Finally, open entry would eliminate administrative delays and/or opportunity costs associated with alternative spectrum allocation approaches, such as comparative hearings, lotteries, or auctions (27).

Unlicensed Spectrum

The Federal Communications Commission (FCC) has implemented in the US regulations for an unlicensed allocation of the 1910 to 1930 MHz PCS band: a spectrum etiquette provides for resource sharing among dissimilar technologies. Under the etiquette, terminals must satisfy a series of access rules on the frequency to be selected, the amount of bandwidth utilized, radiated power, and when to access the spectrum. Compatibility issues of FWA FDD systems in 1910 to 1930 MHz on licensed and unlicensed PCS are at this moment the subject of a study group at the Inter-American Telecommunication Commission (CITEL) (28). Some of the initiatives recommend Time Division Duplex (TDD) use for unlicensed applications only (29).

SIMULATION ANALYSIS ON OPEN-ACCESS DCA (19)

To assess the performance of DCA within a wireless system we used a simulation algorithm that builds on a model previously developed by GTE Laboratories (30) and further incorporates autonomous reuse partitioning (ARP) and transmitter power control (TPC) algorithms. The approach we have selected was based on a discrete-event time-driven Monte Carlo simulation, which is a useful tool for modeling complex large systems at a level unattainable by conventional analytical tools. The model assumes a Poisson process for calls arrivals with no reattempts. Main assumptions are listed in Table 2.

Other key assumptions follow: Users are fixed or quasistationary, inter- and intracell hand-offs are not explicitly modeled, hand-offs are not addressed. The model is based on nonorthogonal coordinates with axis at an angle of 60°, and call attempts and interference effects are simulated over an 8×8 grid of equally sized hexagonal cells. Calls originate at one of 64 discrete points uniformly distributed throughout each cell. Cells fold over onto a torus to avoid edge effects. Signal strength is assumed to follow a fourth-order propagation rule. Cell layouts of competing operators are offset with respect to each other to evaluate system performance under noncollocated scenarios. Adjacent channel interference effects are neglected given that a narrow-band solution was selected. This could not be ignored in the case of broad-band DS-CDMA channels (31).

The simulation assumes a frequency reuse based on C/I service quality figures for second-generation digital technologies (C/I = 9 dB or better) such as IS-136 and GSM1900 (32,33). With fixed channel assignment, C/I = 9 dB would be equivalent to a reuse distance of $\sigma = 3R$ and a cluster size of $K = 3$ ($\sigma/R = \sqrt{3K} = 3$).

Channel Assignment Strategies

The simulation assumes that both mobile units and base stations search through a list of channels in both directions: up link and down link. Channels are assigned if their C/I ratio exceeds a predefined threshold in accordance with one of the two following rules:

1. Random channel selection
   a. An incoming call is assigned an idle channel at random. Channels are searched afterwards in numerical order until finding the first available one that satisfies minimum C/I criteria in both, the forward (base-to-mobile) and reverse (mobile-to-base) links.
   b. If no channel is found that satisfies the C/I criteria, the call is blocked.
2. Autonomous reuse partitioning
   a. The system keeps an ordered list of channels 1 through N. It attempts to allocate an incoming call on the first channel and then keeps searching until selecting the first idle channel that satisfies the C/I threshold for both the forward (base-to-mobile) and reverse (mobile-to-base) links.
   b. If there is no channel that satisfies the criteria, the call is blocked.

Table 2. Model Assumptions

Exponential call interarrival and call-holding times
Blocked calls lost
Homogeneous traffic spatial distribution
Ideal control of received power level
Frequency-division duplex (FDD) channels
Asymmetrical up- and down-link interference
50 available channels
Dynamic channel assignment with TPC and ARP

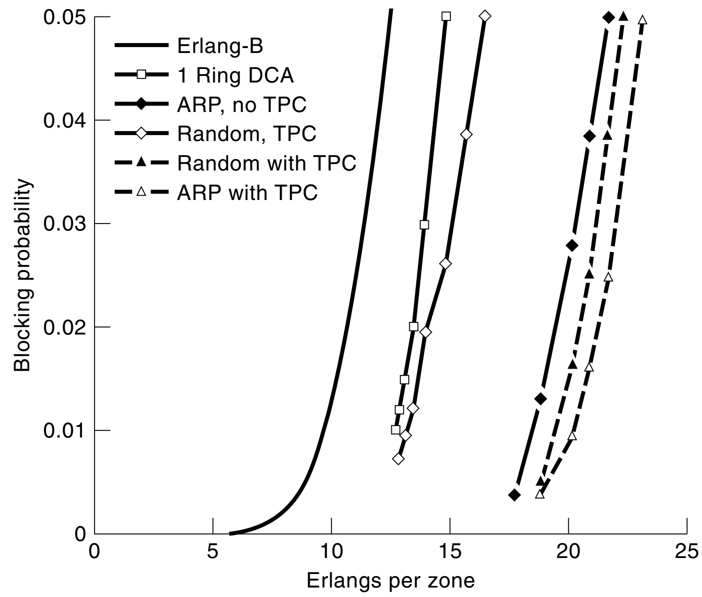

Figure 34. Comparative performance of FCA (Erlang-B), against conventional DCA policies, such as random channel selection and autonomous reuse partitioning, for 50 duplex channels and C/I = 11.32 dB.

Multiple Carriers Simulation

In Fig. 34, we compare the properties of ARP against other resource management techniques such as fixed channel assignment (Erlang-B approximation), minimum reuse distance DCA (one ring buffering ad hoc approximation) (34), and random channel selection with and without TPC. Results show particular ARP capacity gains derived from channel reuse at minimum distances in accordance to the strength of received carrier signals. The impact of TPC is less dramatic when combined with ARP because the algorithm already compensates implicitly for distance.

Interference Feedback with Calls in Progress

Calls in progress in a DCA system may experience co-channel interference from subsequent call arrivals in neighboring cells, which may lower system performance to unacceptable levels (Interference feedback) (35). Escape mechanisms such as intracell hand-offs can provide additional system protection against outages. The number of intracell hand-offs can be reduced by setting an adequate protection margin above the minimal acceptable threshold to prevent interference effects.

Intracell hand-offs are traffic dependent and could be considered as independent new arrivals, that force the system to handle an increased number of calls. Increasing the channel selection threshold also decreases available capacity. Calls may be dropped while in progress if no available channel is found (36). Call dropping probabilities could improve if a portion of the available channels is devoted exclusively to hand-offs (36). A figure of merit should consider blocking probability adjusted by the percentage of calls dropped as a result of unsuccessful intracell hand-offs.

Eriksson (37) simulated the effects of intracell hand-offs and reported a success rate for outage-related hand-offs above 99%. For the simulation we selected a call threshold $C/I >$ 11.32 dB.

Simulation Results

We simulated performance of open-access PCS for a system with four competing operators sharing spectrum through a common air interface (CAI) and DCA. Simulation results show that a system with multiple operators sharing spectrum through DCA is as efficient as a single operator, even under uneven traffic loads. Figure 35 provides a base case to evaluate trunking inefficiencies of a system with evenly shared traffic as compared to exclusive bandwidth allocations.

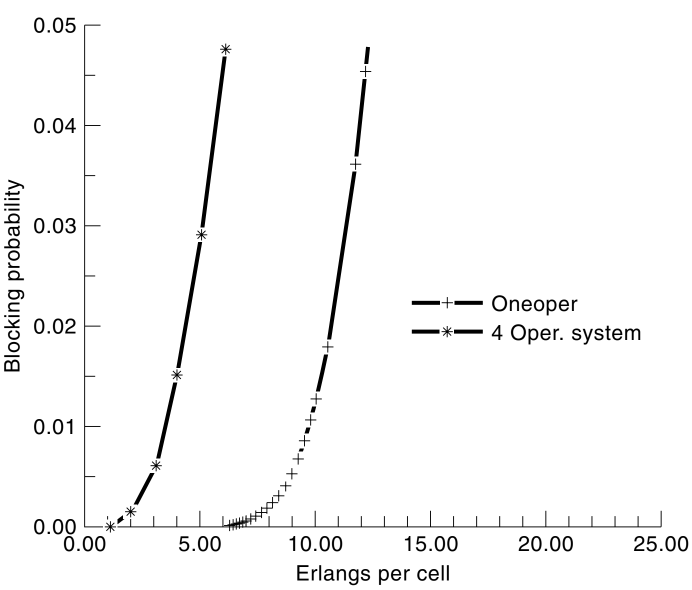

Figure 35. Trunking inefficiencies for FCA, with 50 available channels, three-cell reuse pattern. Theoretical performance of a single operator (Oneoper) against system behavior (4Oper.System) for four simultaneous operators.

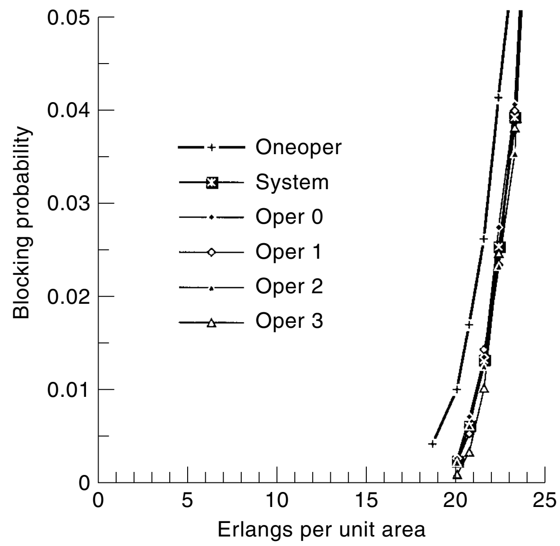

Figure 36. ARP DCA for four noncollocated operators, and cell sites fully loaded with 50 transceivers. C/I = 11.32 dB, transmitter power control.

Blocking probability is plotted against traffic in erlangs per unit area. *Oneoper* represents a single operator; *4Oper.System* represents the performance per operator in a block allocations system with four FCA operators. As each operator receives one-fourth of the available spectrum, the curve yields reduced overall system performance.

Figure 36 shows results of the simulation for unequal traffic distributions among four noncolocated operators, assuming DCA ARP and TPC access policies. This is an alternative way of presenting the same principle of Fig. 33, but in this case overall trunking inefficiencies are more severe as the total number of duplex channels is only 50. MTBA is the mean time between arrivals, AHT is the average holding time, 180 s.

Limitations on the Number of Transceivers Per Cell. Figure 36 represents fully loaded cells with 50 power controlled transceivers. The maximum number of transceivers per cell could be limited to reduce costs and adjacent channel interference effects. Throughout this section we will refer to the maximum number of servers (channels) available in a cell site as MAXCHAN.

Assuming fully loaded cells (50 duplex channels) in Fig. 36, the curve labeled *Oneoper* serves as a reference for the performance of a single DCA operator using ARP. *System* represents the average performance of four wireless operators as a whole. The curves *oper 0, oper 1, oper 2,* and *oper 3* display relative individual performances per operator assuming unequal market shares (operator 0 carries 50% of the total traffic, operator 1 holds 25%, operator 2 handles 16.7%, and finally operator 3 keeps 8.3%).

Assuming FCA and a reuse pattern of $K = 3$ ($C/I = 9$ dB), each base station would be equipped with 17 radios. Figure 37 compares performance for a single operator using DCA ARP and 50 transceivers per cell site to a scenario with four providers deploying cell sites with no more than 14 radios (MAXCHAN = 14. For a 1% GOS, the average system perfor-

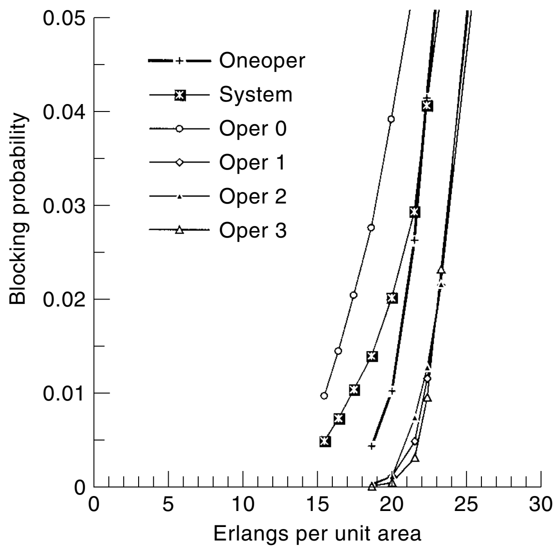

Figure 37. Performance of DCA ARP when the number of active channels (transceivers) is restricted to 14. C/I = 11.32 dB, transmitter power control.

mance with four "transceiver-constrained" operators is slightly less than the performance of a single, unconstrained operator.

Note that the impact of transceiver constraints falls most heavily on the operator handling a larger market share (Oper 0). Operators 1, 2, and 3 are largely indifferent to the restrictions and experience a reduction of traffic at the system level as less interference, consequently these operators can turn a greater portion of call attempts into calls in progress.

Main Conclusions

Our results suggest that dynamic channel assignment can provide an approach to narrow-band spectrum management based on autonomous open access, as long as air interfaces and cell sizes are comparable. The performance of a DCA system with competing operators and collocated cell sites under uneven market shares can be considered as efficient as an exclusive allocation. Furthermore, no negative impact on capacity was found when simulating multiple operators with noncollocated cell centers. We have confirmed that ARP enables decentralized spectrum sharing, avoiding the need for coordination between competing firms. FDD operation avoids the need to synchronize among cells. DCA operation handles trunking inefficiencies derived from sharing the available spectrum among competing service providers. Since all channels are available to any operator, problems of matching bandwidth allocation to market share are solved. We also found that the ARP algorithm is more effective than random channel selection with or without TPC.

Concerning outages produced by autonomous operation, our findings confirm that an additional dB protection margin above the minimum C/I threshold will decrease the number of calls interfered within the system. Systems that incorporate intracell hand-offs enable transfer of interfered calls to unused channels. A small percentage of these calls may be dropped in the process, a tradeoff for the efficiency gains provided by open-access DCA.

Objections to Open Access

Several objections have been raised about the implementation of open access through DCA.

Negative Externalities. In an open-access environment, operators share a common pool of channels. As long-term traffic grows, more channels are occupied and additional cell sites must be deployed to increase system capacity through frquency reuse. Economic efficiency tradeoffs can be expressed as a measure of the incremental cell-site costs required to support total traffic loads under a multioperator scheme, as compared to a single provider.

As the spectrum is shared by DCA the firm investing in new cell sites bears most costs but this investment allows better spectrum reuse, benefiting then all other operators. Consequently, this mismatch of costs and benefits may lead some operators to seek a "free ride" by taking more channels from the common pool rather than adding infrastructure (38). Such resource depletion is known in the literature as *overgrazing* or *tragedy of the commons* (39). Doubts exist on whether, in the absence of government regulations, shared-spectrum operators would coordinate cell-site deployment plans to avoid mutual interference.

Barriers to Technological Innovation. A second objection to open access is "technology lockup" given that channel assignment from a common pool forces operators to share channels through a standardized common air interface. Standards are decided by committees and as such may take time to be approved. Proprietary interfaces can facilitate fast entrance into a market. However, a standardized air interface may also represent advantages. For example, a common AMPS standard allowed competition, economies of scale, and nationwide cellular roaming in the United States. In contrast, it took the FCC almost 15 years to implement the regulations for the North American cellular system.

Technology Evolution and Carrier Fragmentation. DCA could be combined with any set of mutually exclusive orthogonal channels, regardless of the modulation scheme selected: TDMA, FDMA, or CDMA. FDMA implements protection against adjacent channel interference through filters and guard bands. TDMA provides guard bands and separation between logical channels through time. CDMA technologies could be compatible with DCA, but in order to avoid the near–far problem each CDMA carrier must be allocated to one operator at a time through an overlay FDMA scheme. RF hardware is expensive and for that reason digital modulation schemes improve system economics and capacity by bundling several logical channels per RF carrier, thus reducing the number of transceivers. On the other hand, carrier fragmentation produces trunking inefficiencies given that an entire RF carrier would be allocated to handle a single overflow user.

DCA has been considered for microcell deployment under AMPS-DAMPS (Digital AMPS) technologies. With North American TDMA (IS-54, IS-136) a channel bandwidth of 30 kHz accommodates three digital users. TDMA is compatible with open access but requires time-slot synchronization. An entire TDMA/DCA carrier capable of accommodating multiple users can only be assigned to one operator at a time (40). Little impact on grouping inefficiencies is expected from DAMPS DCA as a result of carrier fragmentation, given that it groups only three logical channels on a 30 kHz channel bandwidth (41). DCA is also being discussed as part of the Global System for Mobility (GSM) standard, which divides a 200 kHz RF carrier into eight logical channels. Everitt and Mansfield (42) performed a DCA simulation for a single operator with an eight TDMA channel grouping. Results indicated carrier fragmentation inefficiencies of 50%.

Technologies such as CDMA may improve spectrum efficiency, given that they utilize relatively few wide-band radios, for example, 1.25 MHz for IS-95. But wide-band methods involves channel grouping inefficiencies of CDMA DCA is implemented. To satisfy near–far problem constraints DS-CDMA could be used to support open entry only if operators colocate base stations and keep identical operational thresholds. Public utility models have been suggested with a central entity providing common cell-site infrastructure to competing CDMA operators that deliver their signals to independent antennas (43). Such layered model of competition is at direct variance with current vertical integration industry practices, where competing firms deploy a complete end-to-end network.

Service Differentiation. A main drawback to open-access DCA concerns quality-of-service guarantees: as a consequence of shared use of channels, all operators end up with virtually the same blocking probabilities. This impacts the ability of firms to differentiate on service quality. In addition, actions of competitors (deploying or dismantling cells) impact the engineered grade of service. A possible solution could be based on reserving access to dedicated RF channels for premium service traffic overflow. Regulation could enforce as well preemptive access for emergency and priority calls. Further discussion of such DCA algorithms is beyond the scope of this article.

Tragedy of the Commons Issues with DCA. An open-entry DCA scheme requires incentives for operators to invest in infrastructure as the market grows, allowing operators to trade-off costs against quality of service. Tragedy of the commons problems may be solved by setting a shadow price on utilization of the common resource. For example, regulators might impose fees on spectrum usage based on a figure of merit involving utilized bandwidth (i.e., the number of transceivers per cell site) Effective Isotropic Radiated Power (EIRP). Those operators handling higher traffic demands would be compelled to deploy extra cell sites as the market grows. An alternative approach is a spectrum fee based on the number of cell sites, with more base stations leading to a lower spectrum fee. We note that nothing in the current US FCC policies would prevent the licensee of an exclusive spectrum allocation from subletting its spectrum to multiple operators on a shared basis.

CHANNEL CAPACITY CONSTRAINTS

Wireless technologies must overcome capacity constraints for the provison of bandwidth-hungry services that are beyond basic POTS rates.

Capacity constraints are determined as well by the service definition selected, and transmitted bit rates can vary widely accordingly to such choice. These capacity demands imposed by service evolution may be in clear contrast to the rather limited spectrum that has been allocated for FWA and PCS through international agreements. At the OAS/CITEL PCC.III (Permanent Consulative Committee) a working group has been addressing the determination of capacity and minimum bandwidth requirements for the delivery of FWA basic and enhanced service functionality. Service definitions encompass wireless POTS, POTS −, POTS +, 64k data, ISDN data, wide band, and interactive broad band. Answers to this fundamental question will help to guide spectrum regulators towards the attainment of Universal Service Objectives (USO).

One solution to capacity constraints is the evolution of wireless services towards higher frequencies, at spectrum ranges of 28 GHz, 38 GHz, and beyond. For example, local multipoint distribution systems/local multipoint communications systems (LMDS/LMCS).

From an information-theoretical perspective, orthogonal multiple access schemes such as FDMA, TDMA, or CDMA should yield in principle comparable capacity; however, practical differences exist in their implementation. Much inventive activity today addresses means of serving more subscribers in spectrally congested bands. Second-generation cellular technologies available today are, for example, hierarchical microcells, adaptive channel allocation, co-channel interference cancellation, and smart antennas.

Spectrum capacity is closely related to economic efficiency and could be understood as the number of logical channels available per cell site. Alternatively, one could define a capacity metric based on erlangs per MHz per km^2 or better: cost per erlangs per MHz per km^2.

Figure 38 provides a costs comparison performed by Nortel Technologies among diverse access technologies for a fully loaded mobility network (backhaul and terminal included) under a channel activity of 25 merlangs per subscriber. Capital expenses were not very sensitive to available bandwidth variations from 10 MHz to 20 MHz. Further analysis is needed to explore capacity limits at typical DOTS loads of >100 merlangs/subscriber.

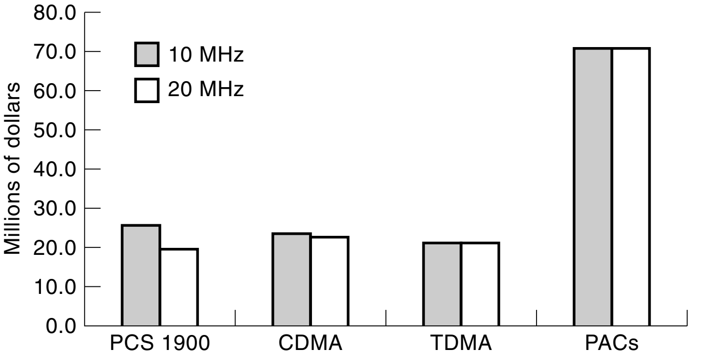

Figure 38. Comparison of total infrastructure and services costs for a wireless project, based on different macro- and microcellular technologies, under a channel activity of 25 merlangs per subscriber.

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