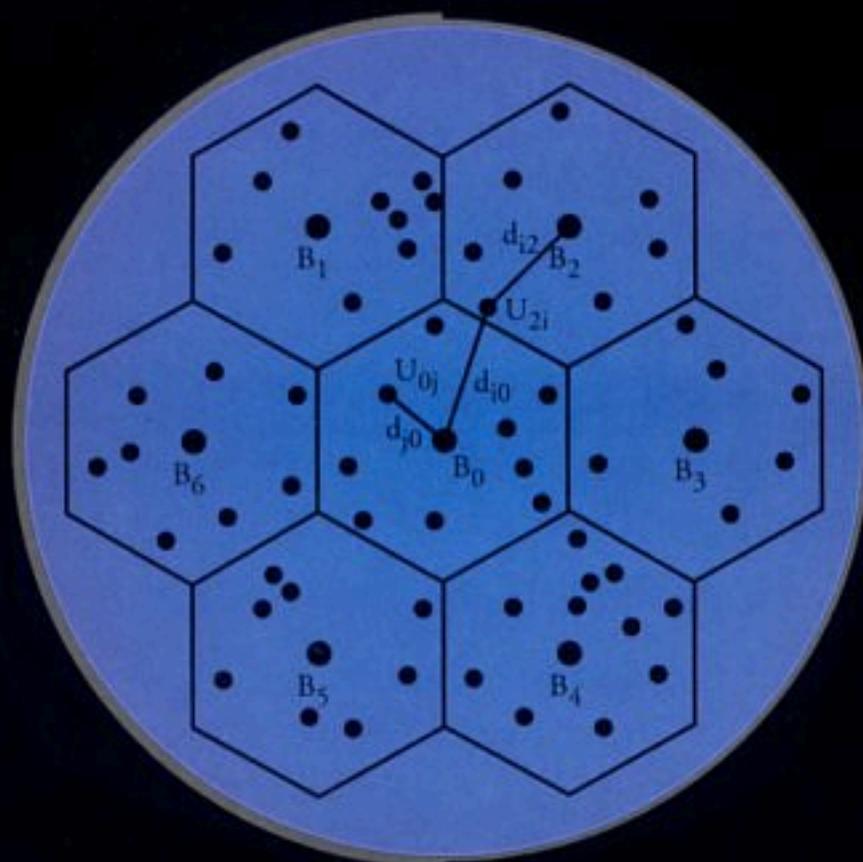


WIRELESS

communications

Principles & Practice



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CHAPTER₁

Introduction to Wireless Communication Systems

The ability to communicate with people on the move has evolved remarkably since Guglielmo Marconi first demonstrated radio's ability to provide continuous contact with ships sailing the English channel. That was in 1897, and since then new wireless communications methods and services have been enthusiastically adopted by people throughout the world. Particularly during the past ten years, the mobile radio communications industry has grown by orders of magnitude, fueled by digital and RF circuit fabrication improvements, new large-scale circuit integration, and other miniaturization technologies which make portable radio equipment smaller, cheaper, and more reliable. Digital switching techniques have facilitated the large scale deployment of affordable, easy-to-use radio communication networks. These trends will continue at an even greater pace during the next decade.

1.1 Evolution of Mobile Radio Communications

A brief history of the evolution of mobile communications throughout the world is useful in order to appreciate the enormous impact that cellular radio and personal communication services (PCS) will have on all of us over the next several decades. It is also useful for a newcomer to the cellular radio field to understand the tremendous impact that government regulatory agencies and service competitors wield in the evolution of new wireless systems, services, and technologies. While it is not the intent of this text to deal with the technological aspects of cellular radio and personal communications, ^{cal} techno-politics are a fundamental driver in the evolution of new technology and services, since radio spectrum usage is controlled by governments, not by service providers, equipment manufacturers, entrepreneurs, or researchers. Progressive involvement in

technology development is vital for a government if it hopes to keep its own country competitive in the rapidly changing field of wireless personal communications.

Wireless communications is enjoying its fastest growth period in history, due to enabling technologies which permit wide spread deployment. Historically, growth in the mobile communications field has come slowly, and has been coupled closely to technological improvements. The ability to provide wireless communications to an entire population was not even conceived until Bell Laboratories developed the cellular concept in the 1960s and 1970s [NobG2], [Mac79], [You79]. With the development of highly reliable, miniature, solid-state radio frequency hardware in the 1970s, the wireless communications era was born. The recent exponential growth in cellular radio and personal communication systems throughout the world is directly attributable to new technologies of the 1970s, which are mature today. The future growth of consumer-based mobile and portable communication systems will be tied more closely to radio spectrum allocations and regulatory decisions which affect or support new or extended services, as well as to consumer needs and technology advances in the signal processing, access, and network areas.

The following market penetration data show how wireless communications in the consumer sector has grown in popularity. Figure 1.1 illustrates how mobile telephony has penetrated our daily lives compared with other popular inventions of the 20th century. Figure 1.1 is a bit misleading since the curve labeled "mobile telephone" does not include non-telephone mobile radio applications, such as paging, amateur radio, dispatch, citizens band (CB), public service, cordless phones, or terrestrial microwave radio systems. In fact, in late 1990, licensed non-cellular radio systems in the U.S. had over 12 million users, more than twice the U.S. cellular user population at that time [FCC91]. Figure 1.1 shows that the first 35 years of mobile telephone saw little market penetration due to high cost and the technological challenges involved, but how, in the past decade, cellular telephone has been accepted by consumers at rates comparable to the television, and the video cassette recorder.

In 1934, 194 municipal police radio systems and 58 state police stations had adopted amplitude modulation (AM) mobile communication systems for public safety in the U.S. It was estimated that 5000 radios were installed in mobile in the mid 1930s, and vehicle ignition noise was a major problem for these early mobile users [Nob62]. In 1935, Edwin Armstrong demonstrated frequency modulation (FM) for the first time, and since the late 1930s, FM has been the primary modulation technique used for mobile communication systems throughout the world. World War II accelerated the improvements of the world's manufacturing and miniaturization capabilities, and these capabilities were put to use in large one-way and two-way consumer radio and television systems following the war.

The number of U.S. mobile users climbed from several thousand in 1940 to

Evolution of Mobile Radio Communications 3 100

C_c
 I_c
 $C_c = a$
 I_c
 C_c
 I_c
 C_c
 I_c

0.!

0 10 20 30 40 50 60 70

Number of years after the first commercial deployment

Figure 1.1

illustrating the growth of mobile telephony as compared to other popular inventions of this century.

86,000 by 1948, 695,000 by 1958, and about 1.4 million users in 1962 [Nob62]. The vast majority of mobile users in the 1960s were not connected to the public-switched telephone network (PSTN), and thus were not able to directly dial telephone numbers from their vehicles. With the boom in CB radio and cordless appliances such as garage door openers and telephones, the number of users of mobile and portable radio in 1995 was about 100 million, or 37% of the U.S. population. Research in 1991 estimated between 25 and 40 million cordless telephones were in use in the U.S., and by the turn of the century this is certain to double [Rap91c]. The number of cellular telephone users grew from 25,000 in 1984 to about 16 million in 1994, and since then, wireless services have been experiencing customer growth rates well in excess of 50% per year. By the end of 1997, there will be nearly 50 million U.S. cellular users. In the first couple of decades of the 21st century, there will be an equal number of wireless and conventional wireline customers throughout the world!

1.2 Mobile Radiotelephone in the U.S.

In 1946, the first public mobile telephone service was introduced in twenty five major American cities. Each system used a single, high-powered transmitter and large tower in order to cover distances of over 50 km in a particular market. The early FM push-to-talk telephone systems of the late 1940s used 120 kHz of RF bandwidth in a half-duplex mode (only one person on the telephone call could talk at a time), even though the actual telephone-grade speech occupies only 3kHz of baseband spectrum. The large RF bandwidth was used because of the difficulty in mass-producing tight RF filters and low-noise, front-end receiver amplifiers. In 1950, the FCC doubled the number of mobile telephone channels per market, but with no new spectrum allocation. Improved technology enabled the channel bandwidth to be cut in half to 60 kHz. By the mid 1960s, the FM bandwidth of voice transmissions was cut to 30 kHz. Thus, there was only a factor of 4 increase in spectrum efficiency due to technology advances from WW II to the mid 1960s. Also in the 1950s and 1960s, automatic channel trunking was introduced and implemented under the label IMTS (Improved Mobile Telephone Service). With IMTS, telephone companies began offering full duplex,

auto-dial, auto-trunking phone systems [CalS8J]. However, IMTS quickly became saturated in major markets. By 1976, the Bell Mobile Phone set-vice for the New York City market (a market of about 10,000,000 people) had only twelve channels and could serve only 543 paying customers. There was a waiting list of over 3,700 people [Ca188], and service was poor due to call blocking and usage over the few channels. IMTS is still in use in the U.S., but is very spectrally inefficient when compared to today's U.S. cellular system.

During the 1950s and 1960s, AT&T Bell Laboratories and other telecommunications companies throughout the world developed the theory and techniques of cellular radiotelephony — the concept of breaking a coverage zone (market) into small cells, each of which reuse portions of the spectrum

to increase spectrum usage at the expense of greater system infrastructure [Mac79]. The basic idea of cellular radio spectrum allocation is similar to that

used by the FCC when it allocates television stations or radio stations with different channels in a region of the country, and then reallocates those same channels to different stations in a completely different part of the country. Channels are only reused when there is sufficient distance between the transmitters to prevent interference. However, cellular relies on reusing the same channels within the same market or service area.

AT&T proposed the concept of a cellular mobile system to the FCC in 1968, although technology was not available to implement cellular telephony until the late 1970s. In 1983, the FCC finally allocated 666 duplex channels (40 MHz of spectrum in the 800 MHz band, each channel having a one-way bandwidth of 30 kHz for a total spectrum occupancy of 60 kHz for each duplex channel) for the U.S. Advanced Mobile Phone System (AMPS) [You79]. According to FCC rules, each city (called a market) was only

Mobile Radiotelephone in the U.S. 5

allowed to have two cellular radio system providers, thus providing a duopoly within each market which would assure some level of competition. As described in Chapters 2 and 10, the radio channels were split equally between the two carriers. AMPS was the first U.S. cellular telephone system, and was deployed in late 1983 by Ameritech in Chicago, IL [Bou91]. In 1989, the FCC granted an additional 166 channels (10 MHz) to U.S. cellular service providers to accommodate the rapid growth and demand. Figure 1.2 illustrates the spectrum currently allocated for U.S. cellular telephone use. Cellular radio systems operate in an interference-limited environment and rely on judicious frequency reuse plans

(which are a function of the market-specific propagation characteristics) and frequency division multiple access (FDMA) to maximize capacity. These concepts will be covered in detail in subsequent chapters of this text.

Reverse Channel Forward Channel

82 4-849 MHz

990 N 1023

0.030N + 825.0

Channel Number

869-894 MHz

Forward Channel I S N 799

0.030(N — 1023) + 825.0 0.030N +

Center Frequency (MHz)

870.0

Reverse Channel I N 799

990 N 1023

0.030(N— 1023) + 870.0

(Channels 800 - 989 are unused)

Figure 1.2

Frequency spectrum allocation for the U.S. cellular radio service. Identically labeled channels in the two bands form a forward and reverse channel pair used for duplex communication between the base station and mobile. Note that the forward and reverse channels in each pair are separated by 45 MHz.

In late 1991, the first U.S. Digital Cellular (USDC) system hardware was installed in major U.S. cities. The USDC standard (Electronic Industry Association Interim Standard 18-54) allows cellular operators to replace gracefully some single-user analog channels with digital channels which support three users in the same 30 kHz bandwidth [EIA90J. In this way, U.S. carriers can gradually phase out AMPS as more users accept digital phones. As discussed in Chapters 8 and 10, the capacity improvement offered by USDC is three times that of AMPS, because digital modulation (1/4 differential quadrature phase shift keying), speech coding, and time division multiple access (TDMA) are used in place of analog FM and FDMA. Given the rate of digital signal processing advancements,

6 Ch. 1 • Introduction to Wireless Communication Systems

speech coding technology will increase the capacity to six users per channel in the same 30 kHz bandwidth within a few years.

A cellular system based on code division multiple access (CDMA) has been developed by Qualcomm, Inc. and standardized by the Telecommunications Industry Association (TIA) as an Interim Standard (15-95). This system supports a variable number of users in 1.25 MHz wide channels using direct sequence spread spectrum. While the analog AMPS system requires that the signal be at least 18 dB above the co-channel interference to provide acceptable call quality, CDMA systems can operate at much larger interference levels because of their inherent interference resistance properties. The ability of CDMA to operate with a much smaller signal-to-noise ratio than conventional narrowband FM techniques allows CDMA systems to use the same set of frequencies in every cell, which provides a large improvement in capacity [Gi1911. Unlike other digital Cellular systems, the Qualcomm system uses a variable rate vocoder with voice activity detection which considerably reduces the required data rate and also the battery drain by the mobile transmitter.

In the early 1990s, a new specialized mobile radio service (SMR) was developed to compete with U.S. cellular radio carriers. By purchasing small groups of radio system

licenses from a large number of independent private radio serviceproviders throughout the country, Nextel and Motorola have formed an extendedSMR (E-SMR) network in the 800 MHz band that could provide capacity and services similar to cellular. Using Motorola's integrated radio system (MITtS), SMRintegrates voice dispatch, cellular phone service, messaging, and data transmission, capabilities on the same network [Fi195].

New Personal Communication Service (PCS) licenses in the 1800/1900MHz band were auctioned by the U.S. Government to wireless providers in early1995, and these promise to spawn new wireless services that will complement, as well as compete with, cellular and SMR. One of the stipulations of the PCSlicense is that a majority of the coverage area be operational before the year 2000. Thus, there is pressure on PCS licensees to "build-out" each market. As many as five PCS licenses are allocated for each major U.S. city (see Chapter 10).

1.3 Mobile Radio Systems Around the World

Many mobile radio standards have been developed for wireless systems throughout the world, and more standards are likely to emerge. Table 1.1through Table 1.3 lists the most common paging, cordless, cellular, and personal communications standards used in North America, Europe, and Japan. The differences between the basic types of wireless systems are described in Section 1.5, and are covered in detail in Chapter 10.

The world's most common paging standard is the Post Office Code Standard Advisory Group (POCSAG) [CC186]j5an82]. POCSAG was developed by British Post Office in the late 1970s and supports binary frequency shift keying (FSK)

Mobile Radio Systems Around the World

T.ble 1.1 Major Mobile Radio Standards In North America Frequency

Standard	Type	Year of Introduction	Multiple Access	Frequency	Modulation	Channel Bandwidth	Other
AMPS	Cellular	1983	FDMA	824-894 MHz	FM	30 kHz	NAME'S Cellular
							1992 FDMA 824-894 MHz FM 10 kHz
USDC	Cellular	1991	TDMA	824-894 MHz	n14-	30 kHz	DQPSK 824-894 MHz GMSK 30 kHz
CDPD	Cellular	1993	FRi		Packet		
							15-95 Cellular/ 1993 CDMA 824-894 MHz QPSK/ 1.25 MHz
PCS							1:8-2.0 GHz
BPSK							

Standard Type	Year of Introduction	Multiple Access		Modulation	
		Frequency	Bandwidth	Frequency	Channel
DCS 1800	1993	TDMA	17.5 MHz	5 MHz	12.5 kHz
PDC Cellular	1993	TDMA	810-1501 MHz	12.5 kHz	12.5 kHz
Nfl Cellular	1979	FDMA	400/800 MHz	12.5 kHz	12.5 kHz
Nfl Paging	1979	FDMA	280 MHz	12.5 kHz	12.5 kHz
PHS Cordless	1993	TDMA	1895-1907 MHz	12.5 kHz	12.5 kHz
NTACS Cellular	1993	FDMA	843-925 MHz	12.5 kHz	12.5 kHz
NEC Paging	1979	FDMA	Several MHz	12.5 kHz	12.5 kHz
JTACS Cellular	1988	FDMA	860-925 MHz	12.5 kHz	12.5 kHz

data and voice transmissions for office and business users. In the US., the PACS standard, developed by Bellcore and Motorola, is likely to be used inside office buildings as a wireless voice and data telephone system or radio local loop. The Personal Handyphone System (PHS) standard supports indoor and local loop applications in Japan. Local loop concepts are explained in Chapter 9.

The world's first cellular system was implemented by the Nippon Telephone and Telegraph company (Nfl) in Japan. The system, deployed in 1979, uses 600 FM duplex channels (25 kHz for each one-way link) in the 800 MHz band. In Europe, the Nordic Mobile Telephone system (NMT 450) was developed in 1981 for the 450 MHz band and uses 25 kHz channels. The European Total Access Cellular System (ETACS) was deployed in 1985 and is virtually identical

Examples of Mobile Radio Systems 9

to the U.S. KMPS system, except that the smaller bandwidth channels result in slight degradation of signal-to-noise ratio (SNR) and coverage range. In Germany, a cellular standard called C-450 was introduced in 1985. The first generation European cellular systems are generally incompatible with one another because of the different frequencies and communication protocols used. These systems are now being replaced by the Pan European digital cellular standard GSM (Global System for Mobile) which was first deployed in 1990 in a new 900 MHz band which all of Europe dedicated for cellular telephone service [Mal89]. As discussed in Chapter 10, the GSM standard is gaining worldwide acceptance as the first universal digital cellular system with modern network features extended to each mobile user, and is a strong contender for PCS services above 1800 MHz throughout the world. In Japan, the Pacific Digital Cellular (PDC) standard provides digital cellular coverage using a system similar to North America's USDC.

1.4 Examples of Mobile Radio Systems

Most people are familiar with a number of mobile radio communication systems used in everyday life. Garage door openers, remote controllers for home entertainment equipment, cordless telephones, hand-held walkie-talkies, pagers (also called paging receivers or "beepers"), and cellular telephones are all examples of mobile radio

communication systems. However, the cost, complexity, performance, and types of services offered by each of these mobile systems are vastly different.

The term mobile has historically been used to classify any radio terminal that could be moved during operation. More recently, the term mobile is used to describe a radio terminal that is attached to a high speed mobile platform (e.g. a cellular telephone in a fast moving vehicle) & whereas the term portable describes a radio terminal that can be hand-held and used by someone at walking speed (e.g. a walkie-talkie or cordless telephone inside a home). The term subscriber is often used to describe a mobile or portable user because in most mobile communication systems, each user pays a subscription fee to use the system, and each

user's communication device is called a subscriber unit. In general, the collective group of users in a wireless system are called users or mobiles, even though many of the users may actually use portable terminals. The mobiles communicate to fixed base stations which are connected to a commercial power source and a fixed backbone network. Table 1.4 lists definitions of terms used to describe elements of wireless communication systems.

Mobile radio transmission systems may be classified as simplex, half duplex or full-duplex. In simplex systems, communication is possible in only one direction. Paging systems, in which messages are received but not acknowledged, are simplex systems.

Half-duplex radio systems allow two-way communication, but use the same radio channel for both transmission and reception. This

10 Ch. 1 • Introduction to Wireless Communication Systems Table 1.4 Wireless Communications System

Definitions

Base Station A fixed station in a mobile radio system used for radio communication with mobile stations. Base stations are located at the center or on the edge of a coverage region and consist of radio channels and transmitter and receiver antennas mounted on a tower.

Control Channel Radio channels used for transmission of call setup, call request, call initiation, and other beacon or control purposes.

Forward Channel Radio channel used for transmission of information from the basestation to the mobile.

Full Duplex Communication systems which allow simultaneous two-way communication. Transmission and reception is typically on two different channels (FDD) although new cordless PCS systems are using TDD.

Half Duplex Communication systems which allow two-way communication by using the same radio channel for both transmission and reception. At any given time, the user can only either transmit or receive information.

Handoff The process of transferring a mobile station from one channel or base station to another.

Mobile Station A station in the cellular radio service intended for use while in motion at unspecified locations. Mobile stations may be hand-held personal units (portables) or installed in vehicles (mobiles).

Mobile Switching Center which coordinates the routing of calls in a large service area. In a cellular radio system, the MSC connects the cellular base stations and the mobiles to the PSTN. An MSC is also called a mobile telephone switching office (MTSO).

Page A brief message which is broadcast over the entire service area, usually in a simulcast fashion by many base stations at the same time.

Reverse Channel Radio channel used for transmission of information from the mobile to base station.

Roamer A mobile station which operates in a service area (market) other than that from which service has been subscribed.

Simplex Systems Communication systems which provide only one-way communication.

Subscriber A user who pays subscription charges for using a mobile communications system.

Transceiver A device capable of simultaneously transmitting and receiving radio signals.

means that at any given time, a user can only transmit or receive information.

Constraints like "push-to-talk" and "release-to-listen" are fundamental features of half-duplex systems. Full duplex systems, on the other hand, allow simultaneous radio transmission and reception between a subscriber and a base station, by providing two simultaneous but separate channels (frequency division duplex,

Examples of Mobile Radio Systems 11

or FDD) or adjacent time slots on a single radio channel (time division duplex, or TDD) for communication to and from the user.

Frequency division duplexing (FDD) provides simultaneous radio transmission channels for the subscriber and the base station, so that they both may constantly transmit while simultaneously receiving signals from one another. At the base

station, separate transmit and receive antennas are used to accommodate the two separate channels. At the subscriber unit, however, a single antenna is used for both transmission to and reception from the base station, and a duplexer is used inside the subscriber unit to enable the same antenna to be

used for simultaneous transmission and reception. To facilitate FDD, it is necessary to separate the transmit and receive frequencies by about 5% of the nominal RF frequency, so that the duplexer can provide sufficient isolation while being inexpensively manufactured.

In FDD, a pair of simplex channels with a fixed and known frequency separation is used to define a specific radio channel in the system. The channel used to convey traffic to the mobile user from a base station is called the forward channel, while the channel used to carry traffic from the mobile user to a base station is called the reverse

channel. In the U.S. AMPS standard, the reverse channel has a frequency which is exactly 45 MHz lower than that of the forward channel, Full duplex

mobile radio systems provide many of the capabilities of the standard duplex telephone, with the added convenience of mobility. Full

and half-duplex systems use transceivers for radio communication. FDD is exclusively in analog mobile radio systems and used

is described in more detail in Chapter 8. Time division duplexing (TDD) uses

the fact that it is possible to share a single radio channel in time, so that a portion of the time is used from the to transmit

base station to the mobile, and the remaining time is used to transmit from the mobile to the base station. If the data transmission rate in the channel is much greater than the end-user's data rate, it is possible to store information bursts and provide the appearance of full duplex operation to a user, even though there are not two simultaneous radio transmissions at any instant of time. TDD is only possible with digital transmission formats and digital modulation, and is very sensitive to timing. It is for this reason that TDD has only recently been used, and only for indoor or small area wireless applications where the physical coverage distances (and thus the radio propagation time delay) are much smaller than the many kilometers used in conventional cellular telephone systems.

1.4.1 Paging Systems

Paging systems are communication systems that send brief messages to a subscriber.

Depending on the type of service, the message may be either a numeric message, an alphanumeric message, or a voice message. Paging systems are typically used to notify a subscriber of the need to call a particular telephone

12 Ch. 1 • Introduction to Wireless Communication Systems

number or travel to a known location to receive further instructions. In modern paging systems, news headlines, stock quotations, and faxes may be sent. A message is sent to a paging subscriber via the paging system access number (usually a toll-free telephone number) with a telephone keypad or modem. The issued message is called a page. The paging system then transmits the page throughout the service area using base stations which broadcast the page on a radio carrier. Paging systems vary widely in their complexity and coverage area. While simple paging systems may cover a limited range of 2 km to 5 km, or may even be confined to within individual buildings, wide area paging systems can provide worldwide coverage. Though paging receivers are simple and inexpensive, the transmission system required is quite sophisticated. Wide area paging systems consist of a network of telephone lines, many base station transmitters, and large radio towers that simultaneously broadcast a page from each base station (this is called simulcasting). Simulcast transmitters may be

located within the same service area or in different cities or countries. Paging systems are designed to provide reliable communication to subscribers wherever they are; whether inside a building, driving on a highway, or flying in an airplane. This necessitates large transmitter powers (on the order of kilowatts) and low data rates (a couple of thousand bits per second) for maximum coverage from each base station. Figure 1.3 shows a diagram of a wide area paging system.

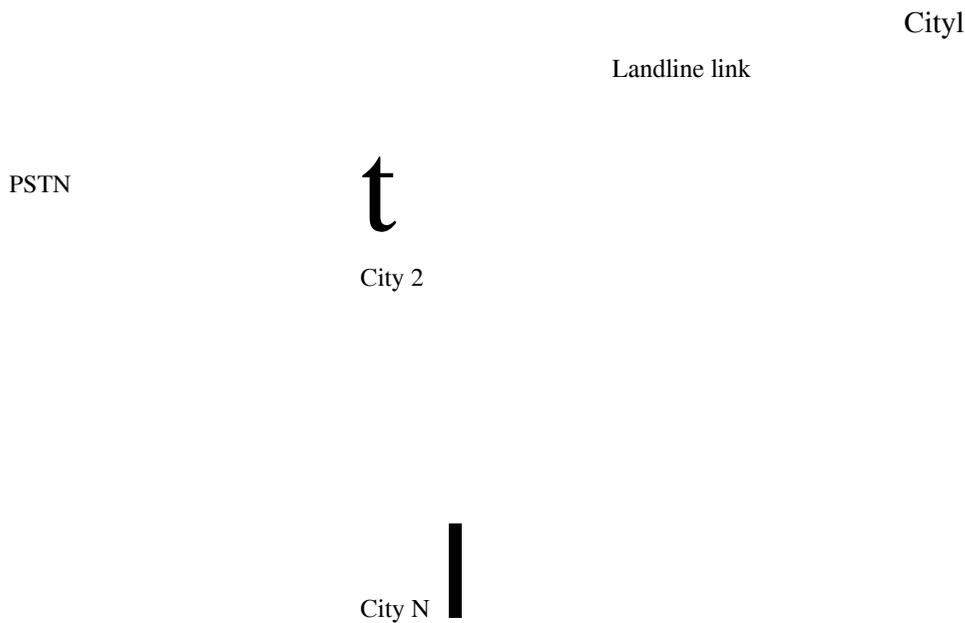


Figure 1.3

Landline link Satellite link

Diagram of a wide area paging system. The paging control center dispatches pages received from the PSTN throughout several cities at the same time.

Example 1.1

Paging systems are designed to provide ultra-reliable coverage, even

inside buildings. Buildings can attenuate radio signals by 20 or 30 dB, making the choice of base station locations difficult for the paging companies. For this reason, paging transmitters are usually located on tall buildings in the center of a city, and simulcasting is used in conjunction with additional base stations located on the perimeter of the city to flood the entire area. Small RF band widths are used to

maximize the signal-to-noise ratio at each paging receiver, so low data rates (6400 bps or less) are used.

1.4.2 Cordless Telephone Systems

Cordless telephone systems are full duplex communication systems that use radio to connect a portable handset to a dedicated base station, which is then connected to a dedicated telephone line with a specific telephone number on the public switched telephone network (PSTN). In first generation cordless telephone systems (manufactured in the 1980s), the portable unit communicates only to the dedicated base unit and only over distances of a few tens of meters. Early cordless telephones operate solely as extension telephones to a transceiver connected to a subscriber line on the PSTN and are primarily for in-home use.

Second generation cordless telephones have recently been introduced which allow subscribers to use their handsets at many outdoor locations within urban centers such as London or Hong Kong. Modern cordless telephones are sometimes combined with paging receivers so that a subscriber may first be paged and then respond to the page using the cordless telephone. Cordless telephone systems provide the user with limited range and mobility, as it is usually not possible to maintain a call if the user travels outside the range of the base station. Typical second generation base stations provide coverage ranges up to a few hundred meters. Figure 1.4 illustrates a cordless telephone system.

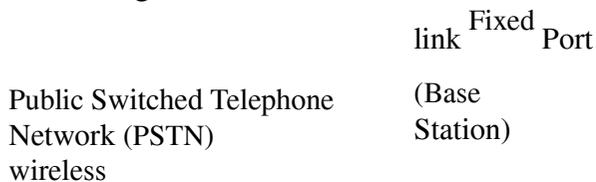


Figure 1.4 Cordless Handset Diagram of a cordless telephone system.

1.4.3 Cellular Telephone Systems

A cellular telephone system provides a wireless connection to the PSTN for any user location within the radio range of the system. Cellular systems accommodate a large number of users over a large geographic area, within a limited frequency spectrum. Cellular radio systems provide high quality service that is often comparable to that of the landline telephone systems. High capacity is achieved by limiting the coverage of each base station transmitter to a small geographic area called a cell so that the same radio channels may be reused by another base station located some distance away. A sophisticated switching technique called a handoff enables a call to proceed uninterrupted when the user moves from one cell to another.

Figure 1.5 shows a basic cellular system which consists of mobile stations, base stations and a mobile switching center (MSC). The Mobile Switching Center is sometimes called a mobile telephone switching office (MTSO), since it is responsible for connecting all mobiles to the PSTN in a cellular system. Each mobile communicates

via radio with one of the base stations and may be handed off to any number of base stations throughout the duration of a call. The mobile station contains a transceiver, an antenna, and control circuitry, and may be mounted in a vehicle or used as a portable hand-held unit. The base stations consist of several transmitters and receivers which simultaneously handle full duplex communications and generally have towers which support several transmitting and receiving antennas. The base station serves as a bridge between all mobile users in the cell and connects the simultaneous mobile calls via telephonelines or microwave links to the MSC. The MSC coordinates the activities of all of the base stations and connects the entire cellular system to the PSTN. A typical MSC handles 100,000 cellular subscribers and 5,000 simultaneous conversations at a time, and accommodates all billing and system maintenance functions, as well. In large cities, several MSCs are used by a single carrier.

Communication between the base station and the mobiles is defined by a standard common air interface (CAI) that specifies four different channels. The channels used for voice transmission from the base station to mobiles are called forward voice channels (FVC) and the channels used for voice transmission from mobiles to the base station are called reverse voice channels (RVC). The two channels responsible for initiating mobile calls are the forward control channels (FCC) and reverse control channels (RCC). Control channels are often called setup channels because they are only involved in setting up a call and moving it to an unused voice channel. Control channels transmit and receive data messages that carry call initiation and service requests, and are monitored by mobiles when they do not have a call in progress. Forward control channels also serve as beacons which continually broadcast all of the traffic requests for all mobiles in the system. As described in Chapter 10, supervisory and data mes

Examples of Mobile Radio Systems 15

Figure 1.5

An illustration of a cellular system. The towers represent base stations which provide radio access between mobile users and the Mobile Switching Center (MSC).

sages are sent in a number of ways to facilitate automatic channel changes

and handoff instructions for the mobiles before and during a call.

Example 1.2

Cellular systems rely on the frequency reuse concept, which requires that the forward control channels (FCCs) in neighboring cells be different. By defining a relatively small number of FCCs as part of the common air interface, cellular phones can be manufactured by many companies which can rapidly scan all of the possible FCCs to determine the strongest channel at any time. Once finding the strongest signal the cellular phone receiver stays "camped" to the particular FCC. By broadcasting the same setup data on all FCCs at the same time, the MSC is able to signal all subscribers within the cellular system and can be certain that any mobile will be signaled when it receives a call via the PSTN.

1.4.3.1 How a Cellular Telephone Call is Made

When a cellular phone is turned on, but is not yet engaged in a call, it first scans the group of forward control channels to determine the one with the strongest signal, and then monitors that control channel until the signal drops below a usable level. At this point it again scans the control channels in search of the strongest base station signal. For each cellular system described in Table 1.1 through Table 1.3, the control channels are defined and standardized over the entire geographic area covered and typically make up about 5% of the total num

16 Ch. 1. Introduction to Wireless Communication Systems

ber of channels available in the system (the other 95% are dedicated to voice and data traffic for the end-users). Since the control channels are standardized and are identical throughout different markets within the country or continent, every phone scans the same channels while idle. When a telephone call is placed to a mobile user, the MSC dispatches the request to all base stations in the cellular system. The mobile identification number (MIN), which is the subscriber's telephone number, is then broadcast as a paging message over all of the forward control channels throughout the cellular system. The mobile receives the paging message sent by the base station which it monitors, and responds by identifying itself over the reverse control channel. The base station relays the acknowledgment sent by the mobile and informs the MSC of the handshake. Then, the MSC instructs the base station to move the call to an unused voice channel within the cell (typically, between ten to sixty voice channels and just one control channel are used in each cell's base station). At this point the base station signals the mobile to change frequencies to an unused forward and reverse voice channel pair, at which point another data message (called an alert) is transmitted over the forward voice channel to instruct the mobile telephone to ring, thereby instructing the mobile user to answer the phone. Figure 1.6 shows the sequence of events involved with connecting a call to a mobile user in a cellular telephone system. All of these events occur within a few seconds and are not noticeable by the user.

Once a call is in progress, the MSC adjusts the transmitted power of the mobile and changes the channel of the mobile unit and base stations in order to maintain call quality as the subscriber moves in and out of range of each base station. This is called a handoff. Special control signaling is applied to

the voice channels so that the mobile unit may be controlled by the base station and the MSC while a call is in progress.

When a mobile originates a call, a call initiation request is sent on the reverse control channel. With this request the mobile unit transmits its telephone number (MIN), electronic serial number (ESN), and the telephone number of the called party. The mobile also transmits a station class mark (SCM) which indicates what the maximum transmitter power level is for the particular user. The cell base station receives this data and sends it to the MSC. The MSC validates the request, makes connection to the called party through the PSTN, and instructs the base station and mobile user to move to an unused forward and reverse voice channel pair to allow the conversation to begin. Figure 1.7 shows the sequence of events involved with connecting a call which is initiated by a mobile user in a cellular system.

All cellular systems provide a service called roaming. This allows subscribers to operate in service areas other than the one from which service is subscribed. When a mobile enters a city or geographic area that is different from its home service area, it is registered as a roamer in the new service area. This is

Examples of Mobile Radio Systems 17

accomplished over the FCC, since each roamer is camped on to a FCC at all times. Every several minutes, the MSC issues a global command over each FCC in the system, asking for all mobiles which are previously unregistered to report their MIN and ESN over the RCC. New unregistered mobiles in the system periodically report back their subscriber information upon receiving the registration request, and the MSC then uses the MIN/ESN data to request billing status from the home location register (HLR) for each roaming mobile. If a particular roamer has roaming authorization for billing purposes, the MSC registers the subscriber as a valid roamer. Once registered, roaming mobiles are allowed to receive and place calls from that area, and billing is routed automatically to the subscriber's home service provider. The networking concepts used to implement roaming are covered in Chapter 9.

1.4.4 Comparison of Common Mobile Radio Systems

Table 1.5 and Table 1.6 illustrate the types of service, level of infrastructure, cost, and complexity required for the subscriber segment and base station segment of each of the five mobile or portable radio systems discussed earlier in this chapter. For comparison purposes, common household wireless remote devices are shown in the table. It is important to note that each of the five mobile radio systems given in Table 1.5 and Table 1.6 use a fixed base station, and for good reason. Virtually all mobile radio communication systems strive to connect a moving terminal to a fixed distribution system of some sort and attempt to look invisible to the distribution system. For example, the receiver in the garage door opener converts the received signal into a simple binary signal which is sent to the switching center of the garage motor. Cordless telephones use fixed base stations so they may be plugged into the telephone line supplied by the phone company — the radio link between the cordless phone base station and the portable handset is designed to behave identically

to the coiled cord connecting a traditional wired telephone handset to the telephone carriage.

Notice that the expectations vary widely among the services, and the infrastructure costs are dependent upon the required coverage area. For the case of low power, hand-held cellular phones, a large number of base stations are required to insure that any phone is in close range to a base station within a city. If base stations were not within close range, a great deal of transmitter power would be required of the phone, thus limiting the battery life and rendering the service useless for hand-held users.

Because of the extensive telecommunications infrastructure of copper wires, microwave line-of-sight links, and fiber optic cables — all of which are fixed — it is highly likely that future land-based mobile communication systems will continue to rely on fixed base stations which are connected to some type of fixed distribution system. However, emerging mobile satellite networks will require orbiting base stations.

Connect the mobile with the existing PSTN.

Transmit the incoming mobile to the specific voice terminal.

Receive the mobile terminal's voice signal.

Begin voice transmission.

Begin voice transmission.

Receive data signals to the specified voice terminal.

Begin voice reception.

Begin transmission.

Figure 1.6 Timing diagram illustrating how a call to a mobile user initiated by a landline subscriber is established.

Write that the mobile has valid

MIN, ESN pair

Trainsits pag^e (MN) for tpcci
fled ma

Receive. call fraⁿ PSTN. Sent^t Ci^a Mark and panes t^o MSC
the mque.ted M^N all base

Receives MN['] an, Station

Acknowledge^e receipt of MN

an^d sands ESN and St. don

G^a

Receives page an^d m*the. the

time^e

RVC

RCC

RVC

PVC

FCC

RCC

FCC

PVC

Bas^e Statioⁿ

Mobil^e

MSC

Dept 'aloe Vms Begat vol^e THOSPIL

Cain I^S mobile with I^S calledpstyaiⁱ thoPrrrq buemote

FCC of algima⁻⁹ b^e 114cr to mov^e mobile tea — of vol^e

Pa, for o.lle^d ligliiemobijot^o move to vol^e Recalva, Pil^e Realva all MkjMjoⁿ 'equet front^t ase Maleⁿ aid vcdfla due lit
mobil^e ae valid MN, ESN —

aid cath. — MN flh ka owⁿ MN. Rees^e t^o monlovce

Begat vale baa- —

Begin vol^e

reapdat

FC^C RC^C FV^C

Saiaaaalnitia floe tequea alon^g with aSsatb^e MN arid
mimbo^r of called paly

illustrating ho^w

tim^e

a call initiated by a mobile is established

Raceivo. call initi⁻ Mien reques an^d MN, ESN, Sta['] US Mai^L

RV^C FC^C

RCC^C

PVC^C

RV^C

Mobile Figure 1.7 Timing diagram

MS^C Bas^e Statioⁿ

20 Ch. 1 • Introduction to Wireless Communication Systems Table 1.5 Comparison of

Mobile Communication Systems — Mobile Station

Service Coverage	Complexity	Hardware	Functionality
Required	structure	Carrier	Frequency
Range	Cost		
TV Control	Low	Low	Low
Garage Opener	Low	Low	Low
Paging	High	High	Low
Cordless	Low	Low	Moderate
Cellular	High	High	High

Table 1.6 Comparison of Mobile Communication Systems — Base Station

Service Coverage Required Complexity Hardware Carrier Functionality Range Infra- Cost Frequency structure

TV Low Low Low Low Infra-red Receiver Remote Control

Garage Low Low Low Low <100 MHz Receiver Door Opener

Paging High High High High <1 GHz Transmitter System

Cordless Low Low Low Moderate c 100 MHz Transceiver Phone

Cellular High High High High < 1 GHz Transceiver Phone

1.5 Trends in Cellular Radio and Personal Communications Since 1989, there has been enormous activity throughout the world to develop personal wireless systems that combine the network intelligence of today's PSTN with modern digital signal processing and RF technology. The concept, called Personal Communication Services (PCS), originated in the United Kingdom when three companies were given spectrum in the 1800 MHz to develop Personal Communication Networks (PCN) throughout Great Britain [Rap91c]. PCN was seen by the U.K. as a means of improving its international competitiveness in the wireless field while developing new wireless systems and

Trends in Cellular Radio and Personal Communications 21

services for citizens. Presently, field trials are being conducted throughout the world to determine the suitability of various modulation; multiple-access, and networking techniques for future PCN and PCS systems.

The terms PCN and PCS are often used interchangeably. PCN refers to a wireless networking concept where any user can make or receive calls, no matter where they are, using a light-weight, personalized communicator. PCS refers to new wireless systems that incorporate more network features and are more personalized than existing cellular radio systems, but which do not embody all of the concepts of an ideal PCN.

Indoor wireless networking products are steadily emerging and promise to become a major part of the telecommunications infrastructure within the next decade. An international standards body, IEEE 802.11, is developing standards for wireless access between computers inside buildings. The European Telecommunications Standard Institute (ETSI) is also developing the 20 Mbps HIPER LAN standard for indoor wireless networks. Recent products such as Motorola's 18 GHz Altair WIN (wireless information network) modem and AT&T's (formerly NCR) waveLAN computer modem have been available as wireless ethernet connections since 1990 and are beginning to penetrate the business world [Tuc93]. Before the end of the 20th century products will allow users to link their phone with their computer within an office environment, as well as in a public setting, such as an airport or train station.

A worldwide standard, the Future Public Land Mobile Telephone

System (FPLMTS) — renamed International Mobile Telecommunication 2000 (IMT-2000) in mid-1995 — is being formulated by the International Telecommunications Union (ITU) which is the standards body for the United Nations, with headquarters in Geneva, Switzerland. The technical group TG 8/1 standards task group is within the ITU's Radiocommunications Sector (ITU-R). ITU-R was formerly known as the Consultative Committee for International Radiocommunications (CCIR). TG 8/1 is considering how future PCNs should evolve and how world wide frequency coordination might be implemented to allow subscriber units to work anywhere in the world. FPLMTS (now IMT-2000) is a third generation

universal, multi-function, globally compatible digital mobile radio system that would integrate paging, cordless, and cellular systems, as well as low earth orbit (LEO) satellites, into one universal mobile system. A total of 230 MHz in frequency bands 1885 MHz to 2025 MHz and 2110 MHz to 2200 MHz has been targeted by the ITU's 1992 World Administrative Radio Conference (WARC). The types of modulation, speech coding, and multiple access schemes to be used in IMT-2000 are yet to be decided.

Worldwide standards are also required for emerging LEO satellite communication systems that are in the design and prototyping stage. Due to the very large areas on earth which are illuminated

by satellite transmitters, satellite based cellular systems will never approach the capacities provided by land-based

22 Ch. 1 • Introduction to Wireless Communication Systems

microcellular systems. However, satellite mobile systems offer tremendous promise for paging, data collection, and emergency communications, as well as for global roaming before IMT-2000 is deployed. In early 1990, the aerospace industry demonstrated the first successful launch of a small satellite on a rocket from an aircraft. This launch technique is more than an order of magnitude less expensive than conventional ground-based launches and can be deployed quickly suggesting that a network of LEOs could be rapidly deployed for wireless communications around the globe. Already, several companies have proposed systems and service concepts for worldwide paging, cellular telephone, and emergency navigation and notification [IEE91].

In emerging nations, where existing telephone service is almost nonexistent, fixed cellular telephone systems are being installed at a rapid rate. This is due to the fact that developing nations are finding it is quicker and more affordable to install cellular telephone systems for fixed home use, rather than install wires in neighborhoods which have not yet received telephone connections to the PSTN.

The world is now in the early stages of a major telecommunications revolution that will provide ubiquitous communication access to citizens, wherever they are. This new field requires engineers who can design and develop new wireless systems, make meaningful comparisons of competing systems, and understand the engineering trade-offs that must be made in any system. Such understanding can only be achieved by mastering the fundamental technical concepts of wireless personal communications. These concepts are the subject of the remaining chapters of this text.

1-6 Problems

- 1.1 Why do paging systems need to provide low data rates? How does a low data rate lead to better coverage?
- 1.2 Qualitatively describe how the power supply requirements differ between mobile and portable cellular phones, as well as the difference between pocket pagers and cordless phones. How does coverage range impact battery life in a mobile radio system?
- 1.3 In simulcasting paging systems, there usually is one dominant signal arriving at the paging receiver. In most, but not all cases, the dominant signal arrives from the transmitter closest to the paging receiver. Explain how the FM capture effect could help reception of the paging receiver. Could the FM capture effect help cellular radio systems? Explain how.
- 1.4 Where would walkie-talkies fit in Tables 1.5 and 1.6? Carefully describe the similarities and differences between walkie-talkies and cordless telephones. Why would consumers expect a much higher grade of service for a cordless telephone system?
 - 1.5 Assume a 1 Amp-hour battery is used on a cellular telephone (often called a cellular subscriber unit). Also assume that the cellular telephone draws 35 mA in idle mode and 250 mA during a call. How long would the phone work (i.e. what is the battery life) if the user leaves the phone on continually and has
 - one 3-minute call every day? every 6 hours? every hour? What is the maximum talk time available on the cellular phone in this example?
- 1.6 Assume a CT2 subscriber unit has the same size battery as the phone in Problem 1.5, but the paging receiver draws 5 mA in idle mode and the transceiver draws 80 mA during a call. Recompute the CT2 battery life for the call rates given in Problem 1.5. Recompute the maximum talk time for the CT2 handset.
- 1.7 Why would one expect the CT2 handset in Problem 1.6 to have a smaller battery drain during transmission than a cellular telephone?
- 1.8 Why is FM, rather than AM, used in most mobile radio systems today? List as many reasons as you can think of, and justify your responses. Consider issues such as fidelity, power consumption, and noise.
- 1.9 List the factors that led to the development of (a) the GSM system for Europe, and (b) the U.S. digital cellular system. Compare and contrast the importance for both efforts to (i) maintain compatibility with existing cellular phones. (ii) obtain spectral efficiency. (iii) obtain new radio spectrum.
- 1.10 Assume that a GSM, an IS-95, and a U.S. digital cellular base station transmit the same power over the same distance. Which system will provide the best SNR at a mobile receiver? What is the SNR improvement over the other two systems? Assume a perfect receiver with only thermal noise present in each of the three systems.
- 1.11 Discuss the similarities and differences between a conventional cellular radio system

and a space-based (satellite) cellular radio system. What are the advantages and disadvantages of each system? Which system could support a larger number of users for a given frequency allocation? Why? How would this impact the cost of service for each subscriber?

1.12 Assume that wireless communication standards can be classified as belonging to one of the following four groups:

High power, wide area systems (cellular)

Low power, local area systems (cordless telephone and PCS)

Low data rate, wide area systems (mobile data)

High data rate, local area systems (wireless LANs)

Classify each of the wireless standards described in Tables 1.1 - 1.3 using these four groups. Justify your answers. Note that some standards may fit into more than one group.

1.13 Discuss the importance of regional and international standards organizations such as ITU-R, ETSI, and WARC. What competitive advantages are there in using different wireless standards in different parts of the world? What disadvantages arise when different standards and different frequencies are used in different parts of the world?

1.14 Based on the proliferation of wireless standards throughout the world, discuss how likely it is for IMT-2000 to be adopted. Provide a detailed explanation, along with probable scenarios of services, spectrum allocations, and cost.

24 Ch. 1 Introduction to Wireless Communication Systems

CHAPTER 2

The Cellular Concept — System Design Fundamentals

The design objective of early mobile radio systems was to achieve a large coverage area by using a single, high powered transmitter with an antenna mounted on a tall tower. While this approach achieved very good coverage, it also meant that it was impossible to reuse those same frequencies throughout the system, since any attempts to achieve frequency reuse would result in interference. For example, the Bell mobile system in New York City in the 1970s could only support a maximum of twelve simultaneous calls over a thousand square miles [Cal88]. Faced with the fact that government regulatory agencies could not make spectrum allocations in proportion to the increasing demand for mobile services, it

became imperative to restructure the radio telephone system to achieve high capacity with limited radio spectrum, while at the same time covering very large areas.

2.1 Introduction

The cellular concept was a major breakthrough in solving the problem of spectral congestion and user capacity. It offered very high capacity in a limited spectrum allocation without any major technological changes. The cellular concept is a system level idea which calls for replacing a single, high power transmitter (large cell) with many low power transmitters (small cells), each providing coverage to only a small portion of the service area. Each base station is allocated a portion of the total number of channels available to the entire system, and nearby base stations are assigned different groups of channels so that all the available channels are assigned to a relatively small number of neighboring base stations. Neighboring base stations are assigned different groups of channels so that the interference between base stations (and the mobile users

under their control) is minimized. By systematically spacing base stations and their channel groups throughout a market, the available channels are distributed throughout the geographic region and may be reused as many times as necessary, so long as the interference between co-channel stations is kept below acceptable levels.

As the demand for service increases (i.e., as more channels are needed within a particular market), the number of base stations may be increased (along with a corresponding decrease in transmitter power to avoid added interference), thereby providing additional radio capacity with no additional increase in radio spectrum. This fundamental principle is the foundation for all modern wireless communication systems, since it enables a fixed number of channels to serve an arbitrarily large number of subscribers by reusing the channels throughout the coverage region. Furthermore, the cellular concept allows every piece of subscriber equipment within a country or continent to be manufactured with the same set of channels, so that any mobile may be used anywhere within the region.

2.2 Frequency Reuse

Cellular radio systems rely on an intelligent allocation and reuse of channels throughout a coverage region [Oet83]. Each cellular base station is allocated a group of radio channels to be used within a small geographic area called a cell. Base stations in adjacent cells are assigned channel groups which contain completely different channels than neighboring cells. The base station antennas are designed to achieve the desired coverage within the particular cell. By limiting the coverage area to within the boundaries of a cell, the same group of channels may be used to cover different cells that are separated from one another by distances large enough to keep interference levels within tolerable limits. The design process of selecting and allocating channel groups for all of the cellular base stations within a system is called frequency reuse or frequency planning [Mac79].

Figure 2.1 illustrates the concept of cellular frequency reuse, where cells labeled with the same letter use the same group of channels. The frequency reuse plan is overlaid upon a map to indicate where different frequency channels are used. The hexagonal cell shape shown in Figure 2.1 is conceptual and is a simplistic model of the radio coverage for each base station, but it has been universally adopted since the hexagon permits easy and manageable analysis of a cellular system. The actual radio coverage of a cell is known as the footprint and is determined from field measurements or propagation prediction models. Although the real footprint is amorphous in nature, a regular cell shape is needed for systematic system design and adaptation for future growth. While it might seem natural to choose a circle to represent the coverage area of a base station, adjacent circles can not be overlaid upon a map without leaving gaps or

Figure 2.1

Illustration of the cellular frequency reuse concept. Cells with the same letter use the same set of frequencies. A cell cluster is outlined in bold and replicated over the coverage area. In this example, the cluster size, N , is equal to seven, and the frequency reuse factor is $1/7$ since each cell contains one-seventh of the total number of available channels.

creating overlapping regions. Thus, when considering geometric shapes which cover an entire region without overlap and with equal area, there are three sensible choices: a square; an equilateral triangle; and a hexagon. A cell must be designed to serve the weakest mobiles within the footprint, and these are typically located at the edge of the cell. For a given distance between the center of a polygon and its farthest perimeter points, the hexagon has the largest area of the three. Thus, by using the hexagon geometry the fewest number of cells can cover

a geographic region, and the hexagon closely approximates a circular radiation pattern which would occur for an omni-directional base station antenna and freespace propagation. Of course, the actual cellular footprint is determined by the contour in which a given transmitter serves the mobiles successfully.

When using hexagons to model coverage areas, base station transmitters are depicted as either being in the center of the cell (center-excited cells) or on three of the six cell vertices (edge-excited cells). Normally, omni-directional antennas are used in center-excited cells and sectored directional antennas are used in corner-excited cells. Practical considerations usually do not allow base stations to be placed exactly as they appear in the hexagonal layout. Most system designs permit a base station to be positioned up to one-fourth the cell radius away from the ideal location.

28 Ch. 2 • The Cellular Concept — System Design Fundamentals

To understand the frequency reuse concept, consider a cellular system which has a total of S duplex channels available for use. If each cell is allocated a group of k channels ($k \leq S$), and if the S channels are divided among N cells into unique and

disjoint channel groups which each have the same number of channels, the total number of available radio channels can be expressed as

$$S = kN \quad (2.1)$$

The N cells which collectively use the complete set of available frequencies is called a cluster. If a cluster is replicated M times within the system, the total number of duplex channels, C , can be used as a measure of capacity and is given

$$C = MkN = MS \quad (2.2)$$

As seen from equation (2.2), the capacity of a cellular system is directly proportional to the number of times a cluster is replicated in a fixed service area. The factor N is called the cluster size and is typically equal to 4, 7, or 12. If the cluster size N is reduced while the cell size is kept constant, more clusters are required to cover a given area and hence more capacity (a larger value of C) is achieved. A large cluster size indicates that the ratio between the cell radius and the distance between co-channel cells is large. Conversely, a small cluster size indicates that co-channel cells are located much closer together. The value for N is a function of how much interference a mobile or base station can tolerate while maintaining a sufficient quality of communications. From a design viewpoint, the smallest possible value of N is desirable in order to maximize capacity over a given coverage area (i.e., to maximize C in equation (2.2)). The frequency reuse factor of a cellular system is given by $1/N$, since each cell within a cluster is only assigned $1/N$ of the total available channels in the system.

Due to the fact that the hexagonal geometry of Figure 2.1 has exactly six equidistant neighbors and that the lines joining the centers of any cell and each of its neighbors are separated by multiples of 60 degrees, there are only certain cluster sizes and cell layouts which are possible [Mac79]. In order to tessellate — to connect without gaps between adjacent cells — the geometry of hexagons is such that the number of cells per cluster, N , can only have values which satisfy equation (2.3).

$$N = i^2 + ij + j^2 \quad (2.3)$$

where i and j are non-negative integers. To find the nearest co-channel neighbors of a particular cell, one must do the following: (1) move i cells along any chain of hexagons and then (2) turn 60 degrees counter-clockwise and move j cells. This is illustrated in Figure 2.2 for $i = 3$ and $j = 2$ (example, $N = 19$).

Example 2.1

If a total of 33 MHz of bandwidth is allocated to a particular FDD cellular telephone system which uses two 25 kHz simplex channels to provide full duplex

Figure 2.2

Method of locating co-channel cells in a cellular system. In this example, $N = 19$ (i.e., $i = 3, j = 2$). [Adapted from [OetS3I © IEEE).

voice and control channels, compute the number of channels available per cell if a system uses (a) 4-cell reuse, (b) 7-cell reuse (c) 12-cell reuse. If 1 MHz of the allocated spectrum is dedicated to control channels, determine an equitable distribution of control channels and voice channels in each cell for each of the three systems.

Solution to Example 2.1

Given:

Total bandwidth = 33 MHz

Channel bandwidth = 25 kHz $\times 2$ simplex channels = 50 kHz/duplex channel Total

available channels = $33,000/50 = 660$ channels

(a) For $N = 4$,

total number of channels available per cell = $660/4 = 165$ channels.

(b) For $N = 7$,

total number of channels available per cell = $660/7 \approx 95$ channels.

(c) For $N = 12$,

total number of channels available per cell = $660/12 = 55$ channels.

A 1 MHz spectrum for control channels implies that there are $1000/50 = 20$ control channels out of the 660 channels available. If we evenly distribute the control and voice channels, simply allocate the same number of channels in each cell wherever possible.

Here, the 660 channels must be evenly distributed to each cell within the cluster. In practice, only the 640 voice channels would be allocated, since the control channels are

as 1 per cell.

allocated separately (a) For $N = 4$, we can have 5 control channels

and 160 voice channels per cell. In practice, however, each cell only needs a single control channel (the control

than the voice channels). Thus, one control channel and 160 voice channels would be assigned to each cell. (b) For $N = 7$, 4 cells with 3 control channels and 92 voice channels, 2 cells with 3 control channels and 90 voice channels, and 1 cell with 2 control channels and 92 voice channels could be allocated. In practice, however, each cell would have one control channel, four cells would have 91 voice channels, and three cells would have 92 voice channels. (c) For $N = 12$, we can have 8 cells with 2 control channels and 53 voice channels, and 4 cells with 1 control channel and 54 voice channels each. In an actual system, each cell would have 1 control channel, 8 cells would have 53 voice channels, and 4 cells would have 54 voice channels.

2.3 Channel Assignment Strategies

For efficient utilization of the radio spectrum, a frequency reuse scheme that is consistent with the objectives of increasing capacity and minimizing interference is required. A variety of channel assignment strategies have been developed to achieve these objectives. Channel assignment strategies can be classified as either fixed or dynamic. The choice of channel assignment strategy impacts the performance of the system, particularly as to how calls are managed when a mobile user is handed off from one cell to another [Thk911, [LiC93], [Sun94J, [Rap93b].

In a fixed channel assignment strategy; each cell is allocated a predetermined set of voice channels. Any call attempt within the cell can only be served by the unused channels in that particular cell. If all the channels in that cell are occupied, the call is blocked and the subscriber does not receive service. Several variations of the fixed assignment strategy exist. In one approach, called the borrowing strategy, a cell is allowed to borrow channels from a neighboring cell if all of its own channels are already occupied. The mobile switching center (MSC) supervises such borrowing procedures and ensures that the borrowing of a channel does not disrupt or interfere with any of the calls in progress in the donor cell.

In a dynamic channel assignment strategy, voice channels are not allocated to different cells permanently. Instead, each time a call request is made, the serving base station requests a channel from the MSC. The switch then allocates a channel to the requested cell following an algorithm that takes into account the likelihood of fixture blocking within the cell, the frequency of use of the candidate channel, the reuse distance of the channel, and other cost functions.

Accordingly, the MSC only allocates a given frequency if that frequency is not presently in use in the cell or any other cell which falls within the minimum restricted distance of frequency reuse to avoid co-channel interference. Dynamic channel assignment reduce the likelihood of blocking, which increases the trunking capacity of the system, since all the available channels in a market are accessible to all of the cells. Dynamic channel assignment strategies require the MSC

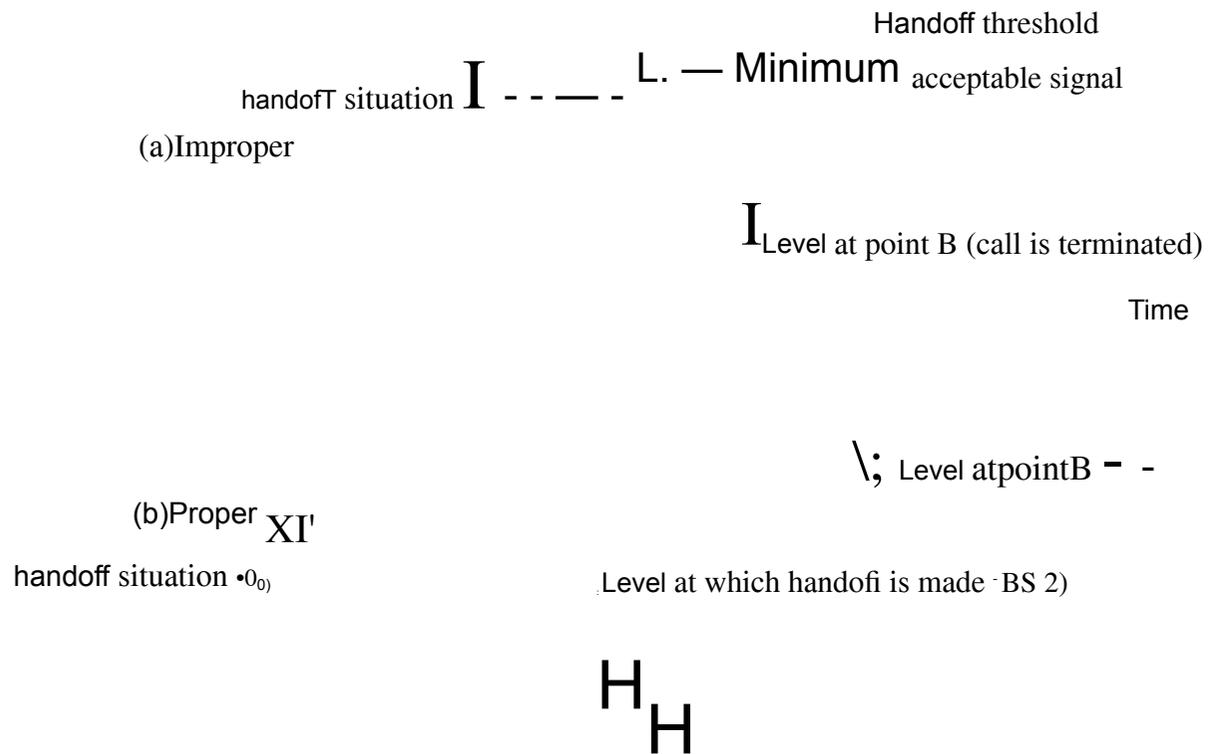


Figure 2.3

Illustration of a handoff scenario at cell boundary.

to collect real-time data on channel occupancy, traffic distribution, and radio signal strength indications (RSSI) of all channels on a continuous basis. This increases the storage and computational load on the system but provides the advantage of increased channel utilization and decreased probability of a blocked call.

2.4 Handoff Strategies

When a mobile moves into a different cell while a conversation is in progress, the MSC automatically transfers the call to a new channel belonging to the new base station. This handoff operation not only involves a new base station, but also requires that the voice and control signals be allocated

Processing handoffs is an important task in any cellular radio system. Many handoff strategies prioritize handoff requests over call initiation requests when allocating unused channels in a cell site. Handoffs must be performed successfully and as infrequently as possible, and be imperceptible to the users. In order to meet these requirements, system designers must specify an optimum signal level at which to initiate a handoff. Once a particular signal level is specified as the minimum usable signal for acceptable voice quality at the base station receiver (normally taken as between -90 dBm and -100 dBm), a slightly stronger signal level is used as a threshold at which a handoff is made. This margin, given by $A = \text{minimum usable}$, cannot be too large or too small. If A is too large, unnecessary handoffs which burden the MSC may occur, and if A is too small, there may be insufficient time to complete a handoff before a call is lost due to weak signal conditions. Therefore, A is chosen carefully to meet these conflicting requirements. Figure 2.3 illustrates a handoff situation. Figure 2.3(a) demonstrates the case where a handoff is not made and the signal drops below the minimum acceptable level to keep the channel active. This dropped call event can happen when there is an excessive delay by the MSC in assigning a handoff, or when the threshold λ is set too small for the handoff time in the system. Excessive delays may occur during high traffic conditions due to computational loading at the MSC or due to the fact that no channels are available on any of the nearby base stations (thus forcing the MSC to wait until a channel in a nearby cell becomes free).

In deciding when to handoff, it is important to ensure that the drop in the measured signal level is not due to momentary fading and that the mobile is actually moving away from the serving base station. In order to ensure this, the base station monitors the signal level for a certain period of time before a handoff is initiated. This running average measurement of signal strength should be optimized so that unnecessary handoffs are avoided, while ensuring that necessary handoffs are completed before a call is terminated due to poor signal level.

The length of time needed to decide if a handoff is necessary depends on the speed at which the vehicle is moving. If the slope of the short-term average received signal level in a given time interval is steep, the handoff should be made quickly. Information about the vehicle speed, which can be useful in handoff decisions, can also be computed from the statistics of the received short-term fading signal at the base station.

The time over which a call may be maintained within a cell, without

hand off, is called the dwell time [Rap93b]. The dwell time of a particular user is governed by a number of factors, which include propagation, interference, distance between the subscriber and the base station, and other time varying effects. Chapter 4 shows that even when a mobile user is stationary, ambient motion in the vicinity of the base station and the mobile can produce fading, thus even a stationary subscriber may have a random and finite dwell time. Analysis in

Handoff Strategies

[Rap93b] indicates that the statistics of dwell time vary greatly, depending on the speed of the user and the type of radio coverage. For example, in mature cells which provide coverage for vehicular highway users, most users tend to have a relatively constant speed and travel along fixed and well-defined paths with good radio coverage. In such instances, the dwell time for an arbitrary user is a random variable with a distribution that is highly concentrated about the mean dwell time. On the other hand, for users in dense, cluttered microcell environments, there is typically a large variation of dwell time about the mean, and the dwell times are typically shorter than the cell geometry would otherwise suggest. It is apparent that the statistics of dwell time are important in the practical design of handoff algorithms [LiC93], [Sun94], [Rap93b].

In first generation analog cellular systems, signal strength measurements are made by the base stations and supervised by the MSC. Each base station constantly monitors the signal strengths of all of its reverse voice channels to determine the relative location of each mobile user with respect to the base station tower. In addition to measuring the RSSI of calls in progress within the cell, a spare receiver in each base station, called the locator receiver, is used to determine signal strengths of mobile users which are in neighboring cells. The locator receiver is controlled by the MSC and is used to monitor the signal strength of users in neighboring cells which appear to be in need of handoff and reports all RSSI values to the MSC. Based on the locator receiver signal strength information from each base station, the MSC decides if a handoff is necessary or not.

In second generation systems that use digital TDMA technology, handoff decisions are mobile assisted. In mobile assisted handoff (MAHO), every mobile station measures the received power from surrounding base stations and continually reports the results of these measurements to the serving base station. A handoff is initiated when the power received from the base station of a neighboring cell begins to exceed the power received from the current base station by a certain level or for a certain period of time. The MAHO method enables the call to be handed over between base stations at a much faster rate than in first^{gen} generation analog systems since the handoff measurements are made by each mobile, and the MSC no longer constantly monitors signal strengths. MAHO is particularly suited for microcellular environments where

are more frequent. During the course of a call, if a mobile moves from handoffs

one cellular system to a different cellular system controlled by a different MSC, an intersystem handoff becomes necessary. An MSC engages in an intersystem handoff when a mobile signal becomes weak in a given cell and the MSC cannot find another cell within its system to which it can transfer the call in progress. There are many issues that must be addressed when implementing an intersystem handoff. For instance, a local call may become a long-distance call as the mobile moves out of its home system and becomes a roamer in a neighboring system. Also, compatibility between the two MSCs must be determined before implementing an intersystem handoff. Chapter 9 demonstrates how intersystem handoffs are implemented in practice.

34 Clt 2. The Cellular Concept — System Design Fundamentals

Different systems have different policies and methods for managing hand off requests. Some systems handle handoff requests in the same way they handle originating calls. In such systems, the probability that a handoff request will not be served by a new base station is equal to the blocking probability of incoming calls. However, from the user's point of view, having a call abruptly terminated while in the middle of a conversation is more annoying than being blocked occasionally on a new call attempt. To improve the quality of service as perceived by the users, various methods have been devised to prioritize handoff requests over call initiation requests when allocating voice channels.

2.4.1 Prioritizing Handoffs

One method for giving priority to handoffs is called the guard channel concept, whereby a fraction of the total available channels in a cell is reserved exclusively for handoff requests from ongoing calls which may be handed off into the cell. This method has the disadvantage of reducing the total carried traffic, as fewer channels are allocated to originating calls. Guard channels, however, offer efficient spectrum utilization when dynamic channel assignment strategies, which minimize the number of required guard channels by efficient demand based allocation, are used.

Queuing of handoff requests is another method to decrease the probability of forced termination of a call due to lack of available channels. There is a trade off between the decrease in probability of forced termination and total carried traffic. Queuing of handoffs is possible due to the fact that there is a finite time interval between the time the received signal level drops below the handoff threshold and the time the call is terminated due to insufficient signal level. The delay time and size of the queue is determined from the traffic pattern of the particular service area. It should be noted that queuing does not guarantee a zero probability of forced termination, since large delays will cause the received signal level to drop below the minimum required level to maintain communication and hence lead to forced termination.

2.4.2 Practical Handoff Considerations

In practical cellular systems, several problems arise when attempting to design for a wide range of mobile velocities. High speed vehicles pass through the coverage region of a cell within a matter of seconds, whereas pedestrian users may never need a handoff during a call. Particularly with the addition of microcells to provide capacity, the MSC can quickly become burdened if high speed users are constantly being passed between very small cells. Several schemes have been devised to handle the simultaneous traffic of high speed and

Handoff Strategies 35

low speed users while minimizing the handoff intervention from the MSC. Another practical limitation is the ability to obtain new cell sites. Although the cellular concept clearly provides additional capacity through the addition of cell sites, in practice it is difficult for cellular service providers to obtain new physical cell site locations in urban areas. Zoning laws, ordinances, and other nontechnical barriers often make it more attractive for a cellular provider to install additional channels and base stations at the same physical location of an existing cell, rather than find new site locations. By using different antenna heights (often on the same building or tower) and different power levels, it is possible to provide "large" and "small" cells which are co-located at a single location. This technique is called the umbrella cell approach and is used to provide large area coverage to high speed users while providing small area coverage to users traveling at low speeds. Figure 2.4 illustrates an umbrella cell which is co-located with some smaller microcells. The umbrella cell approach ensures that the number of handoffs is minimized for high speed users and provides additional microcell channels for pedestrian users. The speed of each user may be estimated by the base station or MSC by evaluating how rapidly the short term average signal strength on the RVC changes over time, or more sophisticated algorithms may be used to evaluate and partition users [LICS3]. If a high speed user in the large umbrella cell is approaching the base station, and its velocity is rapidly decreasing, the base station may decide to hand the user into the co-located microcell, without MSC intervention.

Large "umbrella" cell for low speed traffic
Small microcells for high speed traffic

Figure 2.4
The umbrella cell approach.

Another practical handoff problem in microcell systems is known as cell dragging. Cell dragging results from pedestrian users that provide a very strong signal to the base station. Such a situation occurs in an urban environment when there is a line-of-sight (LOS) radio path between the subscriber and the base sta

tion. As the user travels away from the base station at a very slow speed, the average signal strength does not decay rapidly. Even when the user has traveled well beyond the designed range of the cell, the received signal at the base station may be above the handoff threshold, thus a handoff may not be made. This creates a potential interference and traffic management problem, since the user has meanwhile traveled deep within a neighboring cell. To solve the cell dragging problem, handoff thresholds and radio coverage parameters must be adjusted carefully.

In first generation analog cellular systems, the typical time to make a handoff, once the signal level is deemed to be below the handoff threshold, is about 10 seconds. This requires that the value for α be on the order of 6 dB to

12 dB. In new digital cellular systems such as GSM, the mobile assists with the handoff procedure by determining the best handoff candidates, and the handoff, once the decision is made, typically requires only 1 or 2 seconds. Consequently, α is usually between 0 dB and 6 dB in modern cellular systems. The faster handoff process supports a much greater range of options for handling high speed and low speed users and provides the MSC with substantial time to "rescue" a call that is in need of handoff.

Another feature of newer cellular systems is the ability to make handoff decisions based on a wide range of metrics other than signal strength. The co channel and adjacent channel interference levels may be measured at the base station or the mobile, and this information may be used with conventional signal strength data to provide a multi-dimensional algorithm for determining when a handoff is needed.

The IS-95 code division multiple access (CDMA) spread spectrum cellular system described in Chapter 10, provides a unique handoff capability that can not be provided with other wireless systems. Unlike channelized wireless systems that assign different radio channels during a handoff (called a hard handoff), spread spectrum mobiles share the same channel in every cell. Thus, the term handoff does not mean a physical change in the assigned channel, but rather that a different base station handles the radio communication task. By simultaneously evaluating the received signals from a single subscriber at several neighboring base stations, the MSC may actually decide which version of the user's signal is best at any moment in time. This technique exploits macroscopic space diversity provided by the different physical locations of the base stations and allows the MSC to make a "soft" decision as to which version of the user's signal to pass along to the PSTN at any instance [EPad94]. The ability to select between the instantaneous received signals from a variety of base stations is called soft handoff.

Interference is the major limiting factor in the performance of cellular radiosystems. Sources of interference include another mobile in the same cell, a call in progress in a neighboring cell, other base stations operating in the same frequency band, or any noncellular system which inadvertently leaks energy into the cellular frequency band. Interference on voice channels causes cross talk, where the subscriber hears interference in the background due to an undesired transmission. On control channels, interference leads to missed and blocked calls due to errors in the digital signaling. Interference is more severe in urban areas, due to the greater HF noise floor and the large number of base stations and mobiles. Interference has been recognized as a major bottleneck in increasing capacity and is often responsible for dropped calls. The two major types of system-generated cellular interference are co-channel interference and adjacent channel interference. Even though interfering signals are often generated within the cellular system, they are difficult to control in practice (due to random propagation effects). Even more difficult to control is interference due to out-of-band users, which arises without warning due to front end overload of subscriber equipment or intermittent intermodulation products. In practice, the transmitters from competing cellular carriers are often a significant source of out-of-band interference, since competitors often locate their base stations in close proximity to one another in order to provide comparable coverage to customers.

2.5.1 Co-channel Interference and System Capacity

Frequency reuse implies that in a given coverage area there are several cells that use the same set of frequencies. These cells are called co-channel cells, and the interference between signals from these cells is called co-channel interference. Unlike thermal noise which can be overcome by increasing the signal-to-noise ratio (SNR), co-channel interference cannot be combated by simply increasing the carrier power of a transmitter. This is because an increase in carrier transmit power increases the interference to neighboring co-channel cells. To reduce co-channel interference, co-channel cells must be physically separated by a minimum distance to provide sufficient isolation due to propagation.

When the size of each cell is approximately the same, and the base stations transmit the same power, the co-channel interference ratio is independent of the transmitted power and becomes a function of the radius of the cell (B) and the distance between centers of the nearest co-channel cells (D). By increasing the ratio of D/B , the spatial separation between co-channel cells relative to the coverage distance of a cell is increased. Thus interference is reduced from improved isolation of HF energy from the co-channel cell. The parameter Q , called the co-channel reuse ratio, is related to the cluster

(2.4)

A small value of Q provides larger capacity since the cluster size N is small, whereas a large value of Q improves the transmission quality, due to a smaller level of co-channel interference. A trade-off must be made between these two objectives in actual cellular design.

Table 2.1 Co-channel Reuse Ratio for Some Values of N
Cluster Size (N) Co-channel Reuse Ratio(Q)

$i = 1, j = 1$	3 3
$i = 1, j = 2$	7 4.58
$i = 2, j = 2$	12 6
$i = 1, j = 3$	13 6.24

Let i_0 be the number of co-channel interfering cells. Then, the signal-to-interference ratio (S/I or SIR) for a mobile receiver which monitors a forward channel can be expressed as

(2.5)

where S is the desired signal power from the desired base station and i is the interference power caused by the i th interfering co-channel cell base station. If the signal levels of co-channel cells are known, then the S/I ratio for the forward link can be found using equation (2.5).

Propagation measurements in a mobile radio channel show that the average received signal strength at any point decays as a power law of the distance of separation between a transmitter and receiver. The average received power P. at a distance d from the transmitting antenna is approximated by

(2.6)

or

$$Pr(\text{dBm}) = P_0(\text{dBm}) - 10n \log(j) \quad (2.7)$$

where P_0 is the power received at a close-in reference point in the far field region of the antenna at a small distance d_0 from the transmitting antenna, and n is the path loss exponent. Now consider the forward link where the desired signal is the serving base station and where the interference is due to co-channel base stations. If D_i is the distance of the i th interferer from the mobile, the received power at a given mobile due to the i th interfering cell will be proportional to

The path loss exponent typically ranges between 2 and 4 in urban cellular systems [Rap92b].

When the transmit power of each base station is equal and the path loss exponent is the same throughout the coverage area, S/I for a mobile can be approximated as

$$S = (2.8) I E$$

Considering only the first layer of interfering cells, if all the interfering base stations are equidistant from the desired base station and if this distance is equal to the distance D between cell centers, then equation (2.8) simplifies to

$$S = (D/R)^n I$$

Equation (2.9) relates S/I to the cluster size N, which in turn determines the overall capacity of the system from equation (2.2). For example, assume that the six closest cells are close enough to create significant interference and that they are all approximately equal distance from the desired base station. For the U.S. AMPS cellular system which uses FM and 30 kHz channels, subjective tests indicate that sufficient voice quality is provided when S/I is greater than or equal to 18 dB. Using equation (2.9) it can be shown in order to meet this requirement, the cluster size N should be at least 6.49, assuming a path loss exponent $n = 4$. Thus a minimum cluster size of 7 is required to meet an S/I requirement of 18 dB. It should be noted that equation (2.9) is based on the hexagonal cell geometry where all the interfering cells are equidistant from the base station receiver, and hence provides an optimistic result in many cases. For some frequency reuse plans (e.g. N = 4), the closest interfering cells vary widely in their distances from the desired cell.

From Figure 2.5, it can be seen for a 7-cell cluster, with the mobile unit is at the cell boundary, the mobile is a distance D from the two nearest co-channel interfering cells and approximately $D + R/2$, $D - R/2$, and $D + R$ from the other interfering cells in the first tier [Lee86]. Using equation (2.9) and assuming n equals 4, the signal-to-interference ratio for the worst case can be closely approximated as (an exact expression is worked out by Jacobsmeier [Jac94J]).

$$\frac{R^4}{2(D-R)^4 - 2(D+R)^4 + 2D^4}$$

Equation (2.10) can be rewritten in terms of the co-channel reuse ratio Q, as

$$= \frac{1}{2(Q-1)^4} \quad (2.11)$$

For N = 7, the co-channel reuse ratio Q is 4.6, and the worst case S/I is approximated as 49.56 (17 dB) using equation (2.11), whereas an exact solution using equation (2.8) yields 17.8 dB [Jac94]. Hence for a 7-cell cluster, the S/I ratio is slightly

less than 18 dB for the worst case. To design the cellular system for proper performance in the worst case, it would be necessary to increase N to the next largest size, which from equation (2.3) is found to be 12 (corresponding to $i = j = 2$). This obviously entails a significant decrease in capacity, since 12-cell reuse offers a spectrum utilization of $1/12$ within each cell, whereas 7-cell reuse offers a spectrum utilization of $1/7$. In practice, a capacity reduction of $7/12$ would not be tolerable to accommodate for the worst case situation which rarely occurs. From the above discussion it is clear that co-channel interference determines link performance, which in turn dictates the frequency reuse plan and the overall capacity of cellular systems.

Example 2.2

If a signal to interference ratio of 15 dB is required for satisfactory forward channel performance of a cellular system, what is the frequency reuse factor and cluster size that should be used for maximum capacity if the path loss exponent is (a) $n = 4$, (b) $n = 3$? Assume that there are 6 co-channel cells in the first tier, and all of them are at the same distance from the mobile. Use suitable approximations.

Solution to Example 2.2

(a) $n = 4$

First, let us consider a 7-cell reuse pattern.

Using equation (2.4), the co-channel reuse ratio $DIR = 4.583$.

Using equation (2.9), the signal-to-noise interference ratio is given by $S/I =$

$(1/6) \times (4.583)^4 = 75.3 = 18.66$ dB. Since this is greater than the minimum required S/I , $N = 7$ can be used.

b) $n = 3$

First, let us consider a 7-cell reuse pattern.

Using equation (2.9), the signal-to-interference ratio is given by

$$S/I = (1/6) \times (4.583)^3 = 16.04 = 12.05$$
 dB.

Since this is less than the minimum required S/I , we need to use a larger N .

Using equation (2.3), the next possible value of N is 12, ($i = j = 2$).

The corresponding co-channel ratio is given by equation (2.4) as

$$DIR = 6.0.$$

Interference and System Capacity 41

Using equation (2.3) the signal-to-interference ratio is given by

$$S/I = (1/6) \times 36 = 15.56$$
 dB.

Since this is greater than the minimum required S/I , $N = 12$ can be used.

Figure 2.5

Illustration of the first tier of co-channel cells for a cluster size of $N=7$. When the mobile is at the cell boundary (point A), it experiences worst case co-channel interference on the forward channel. The marked distances between the mobile and different co-channel cells are based on approximations made for easy analysis.

2.5.2 Adjacent Channel Interference

Interference resulting from signals which are adjacent in frequency to the desired signal is called adjacent channel interference. Adjacent channel interference results from imperfect receiver filters which allow nearby frequencies to leak into the passband. The problem can be particularly serious if an adjacent channel user is transmitting in very close range to a subscriber's receiver, while the receiver attempts to receive a base station on the desired channel. This is referred to as the near-far effect, where a nearby transmitter (which may or may

42 Ch. 2 . The Cellular Concept — System Design Fundamentals

not be of the same type as that used by the cellular system) captures the receiver of the subscriber. Alternatively, the near-far effect occurs when a mobile close to a base station transmits on a channel close to one being used by a weak mobile. The base station may have difficulty in discriminating the desired mobile user from the "bleedover" caused by the close adjacent channel mobile.

Adjacent channel interference can be minimized through careful filtering and channel assignments. Since each cell is given only a fraction of the available channels, a cell need not be assigned

channels which are all adjacent in frequency. By keeping the frequency separation between each channel in a given cell as large as possible, the adjacent channel interference may be reduced considerably. Thus instead of assigning channels which form a contiguous band of frequencies within a particular cell, channels are allocated such that the frequency separation between channels in a given cell is maximized. By sequentially assigning successive channels in the frequency band to different cells, many channel allocation schemes are able to separate adjacent channels in a cell by as many as N channel bandwidths, where N is the cluster size. Some channel allocation schemes also prevent a secondary source of adjacent channel interference by avoiding the use of adjacent channels in neighboring cell sites.

If the frequency reuse factor is small, the separation between adjacent channels may not be sufficient to keep the adjacent channel interference level within tolerable limits. For example, if a mobile is 20 times as close to the base station as another mobile and has energy spill out of its passband, the signal-to-interference ratio for the weak mobile (before receiver filtering) is approximately

$$= (2.12)$$

For a path loss exponent $n = 4$, this is equal to -52 dB. If the intermediate frequency (IF) filter of the base station receiver has a slope of 20 dB/octave, then an adjacent channel interferer must be displaced by at least six times the pass band bandwidth from the center of the receiver frequency passband to achieve 52 dB attenuation. Here, a separation of approximately six channel bandwidths is required for typical filters in order to provide 0 dB SIR from a close-in adjacent channel user. This implies that a channel separation greater than six is needed to bring the adjacent channel interference to an acceptable level, or tighter base station filters are needed when close-in and distant users share the same cell.

In practice, each base station receiver is preceded by a high Q cavity filter in order to reject adjacent channel interference.

Example 2.3

This example illustrates how channels are divided into subsets and allocated to different cells so that adjacent channel interference is minimized. The United States AMPS system initially operated with 666 duplex channels. In

1989, the FCC allocated an additional 10 MHz of spectrum for cellular services, and this allowed 166 new channels to be added to the AMPS system. There are now 832 channels used in AMPS. The forward channel (870.030 MHz) along with the corresponding reverse channel (825.030 MHz) is numbered as channel 1. Similarly

the forward channel 889.98 MHz along with the reverse channel 844.98 MHz is numbered as channel 666 (see Figure 1.2). The extended band has channels numbered as 667 through 799, and 990 through 1023.

In order to encourage competition, the FCC licensed the channels to two competing operators in every service area, and each operator received half of the total channels. The channels used by the two operators are distinguished as block A and block B channels. Block B is operated by companies which have traditionally provided telephone services (called wireline operators), and Block A is operated by companies that have not traditionally provided telephone services (called nonwireline operators). Out of the 416 channels used by each operator, 395 are voice channels and the remaining 21 are control channels. Channels 1 through 312 (voice channels) and channels 313 through 333 (control channels) are block A channels, and channels 355 through 666 (voice channels) and channels 334 through 354 (control channels) are block B channels. Channels 667 through 716 and 991 through 1023 are the extended Block A voice channels, and channels 717 through 799 are extended Block B voice channels.

Each of the 395 voice channels are divided into 21 subsets, each containing about 19 channels. In each subset, the closest adjacent channel is 21 channels away. In a 7-cell reuse system, each cell uses 3 subsets of channels. The 3 subsets are assigned such that every channel in the cell is assured of being separated from every other channel by at least 7 channel spacings. This channel assignment scheme is illustrated in Table 2.2. As seen in Table 2.2, each cell uses channels in the subsets, $IA + iB + iC$, where i is an integer from 1 to 7. The total number of voice channels in a cell is about 57. The channels listed in the upper half of the chart belong to block A and those in the lower half belong to block B. The shaded set of numbers correspond to the control channels which are standard to all cellular systems in North America.

2.5.3 Power Control for Reducing Interference

In practical cellular radio and personal communication systems the power levels transmitted by every subscriber unit are under constant control by the serving base stations. This is done to ensure that each mobile transmits the smallest power necessary to maintain a good quality link on the reverse channel. Power control not only helps prolong battery life for the subscriber unit, but also dramatically reduces the reverse channel S/I in the system. As shown in Chapters 8 and 10, power control is especially important for emerging CDMA spread spectrum systems that allow every user in every cell to share the same radio channel.

44 Ch. 2 • The Cellular Concept— System Design Fundamentals Table 2.2 AMPS channel allocation for A side and B side carriers

Channel allocation chart for the 832 channel AMPS system

IA 2A 3A 4A 5A 6A 7A IB 213 30 4B S1) 6B 79 IC 3E 442 SC 642 2 3 4 5 6 7 8 9

22 23 24 25 26 27 28 29 30
43 44 45 46 47 48 49 SI

31 32 33 34 35 36 37 38 39 40 41 42 52 53 54 55 56 57 58 59 (4' 61 62 63
64 65 66 67 68 69 70 71 72

10 II II 13 14 IS 16 7 18 19 20 11

85 86 87 88 89 90 91 92 93

73 74 75 76 77 78 79 80 81 82 83 84

94 95 96 97 98 99 00 101 02 103 04 05

26 107 108 09 IID III 112 113 114

115 116 III III 119 120 121 122 123 124 125 126

117 28 129 130 131 132 113 34 35

36 137 III 39 140 141 142 43 144 145 46 147

148 149 150 151 152 153 54 155 56

IS? 158 159 160 161 52 163 164 65 166 67 68

159 170 171 172 173 174 175 176 177

178 179 ISO 181 182 III 184 185 1*6 187 188 189

190 191 192 193 194 195 196 197 198

199 200 201 202 203 204 205 206 207 208 209 213

211 212 213 214 215 216 217 218 219
SIDE

220 221 222 213 224 225 226 227 218 229 230 231

232 233 234 235 236 237 238 239 240

241 242 243 244 245 246 247 248 249 250 251 252

153 254 255 256 251 258 259 260 261

262 26) 264 265 266 267 268 269 270 271 272 273

274 275 276 277 278 279 280 211 282

183 234 285 286 287 288 289 290 291 292 293 294

295 296 297 298 299 300 301 302 303

304 305 306 307 308 309 310 311 312 ...

9narr



630 671 672 673 674 675 676 677 678
667663 669

679 630 631 632 633 684 685 686 681 688 689 690

691 692 693 694 695 696 697 698 699

712 713 714 715 716 - - -

700 701 702 703 704 705 706 707 708 709 710 711 997 992 993 994 995 996 997 998 999 IOIS tool IOGI IOII 1113 IIII IIIS IIIa 1017 IOII 1Q19 1020 IOII 022 1023

1803 1004 1005 III' 087 008 009 1010 IOII
_33

359 360 361 362 363

364 365 366 367 368 369 370 371 371 373 374 375

336 377 378 379 380 381 382 3*3 384 385 386 381 383 389 390 391 392 393 394 395 396 397 398 399 400 401 402 403 404 405 406 407 408 409 410 411 412 413 414

415 416 417 418 419 420 421 421 423 424 425 426 427 428 429 430 431 412 433 434 435 436 437 438 439 440 441 442 443 444 445 446 447 448 449 450 451 452

453 454 455 454 457 458 459 460 461 462 463 464 465 466 467 464 469 470 471 472 473 474 475 476 477 478 479 480 481 482 483 484 485 486 487 488 489 490

491 491 493 494 495 496 497 498 499 500 501

502 503 504 505 506 507 508 509 510 511 512 513 514 515 516 SI? 518 519 520 521 522

523 524 525 526 527 528 529 530 53* 532 533 534 535 536 537 538 539 546 541 542 543 SIDE

544 545 546 547 548 549 550 551 551 553 554 555 556 557 558 559 560 561 562 563 564 565 566 567 568 569 570 571 572 573 574 575 576 577 578 579 580 581 582 583

584 585 585 587 588 589 5% 591 592 593 594 595 596 597 598 599 601 602 608 604 605 606

601 608 609 610 611 612 613 614 615 616 617 611 619 620 621 622 623 624 625 626 627 628 629 630 631 632 633 634 635 636 637 638 639 640 641 642 643 644

645 646 647 648

649 650 651 652 652 654 655 656 657 658 659 660 661 662 663 664 655 656 657 658 659 -- 720 721 721 723 724 725 726 727 728 729 730 731 732

733 734 735 736 737 738 739 740 741 742 743 744 745 746 747 748 749 750 751 92 753 754 755 756 757 75* 759 760 761 762 763 764 765 766 767 76* 769 770 771

772 773 774 775 776 777 778 775 780 781 782 783 784 785 786 787 788 786 790 791 792 793 794 795 796 797 798 799

2.6 Trunking and Grade of Service

Cellular radio systems rely on trunking to accommodate a large number of users in a limited radio spectrum. The concept of trunking allows a large number of users to share the relatively small number of channels in a cell by providing access to each user, on demand, from a pool of available channels. In a trunked radio system, each user is allocated a channel on a per call basis, and upon termination of the call, the previously occupied channel is immediately returned to the pool of available channels.

Trunking exploits the statistical behavior of users so that a fixed number of channels or circuits may accommodate a large, random user community. The telephone company uses trunking theory to determine the number of telephone

circuits that need to be allocated for office buildings with hundreds of telephones, and

this same principle is used in designing cellular radio systems. There is a trade-off between the number of available telephone circuits and the likelihood of a particular user finding that no circuits are available during the peak calling time. As the number of phone lines decreases, it becomes more likely that all circuits will be busy for a particular user. In a trunked mobile radio system, when a particular user requests service and all of the radio channels are already in use, the user is blocked, or denied access to the system. In some systems, a queue may be used to hold the requesting users until a channel becomes available.

To design trunked radio systems that can handle a specific capacity at a specific "grade of service", it is essential to understand trunking theory and queuing theory. The fundamentals of trunking theory were developed by Erlang, a Danish mathematician who, in the late 19th century, embarked on the study of how a large population could be accommodated by a limited number of servers [Bou88]. Today, the measure of traffic intensity bears his name. One Erlang represents the amount of traffic intensity carried by a channel that is completely occupied (i.e. 1 call-hour per hour or 1 call-minute per minute). For example, a radio channel that is occupied for thirty minutes during an hour carries 0.5 Erlangs of traffic.

The grade of service (GOS) is a measure of the ability of a user to access a trunked system during the busiest hour. The busy hour is based upon customer demand at the busiest hour during a week, month, or year. The busy hours for cellular radio systems typically occur during rush hours, between 4 p.m. and 6 p.m. on a Thursday or Friday evening. The grade of service is a benchmark used to define the desired performance of a particular trunked system by specifying a desired likelihood of a user obtaining channel access given a specific number of channels available in the system. It is the wireless designer's job to estimate the maximum required capacity and to allocate the proper number of channels in order to meet the GOS. GOS is typically given as the likelihood that a call is blocked, or the likelihood of a call experiencing a delay greater than a certain queuing time.

A number of definitions listed in Table 2.3 are used in trunking theory to make capacity estimates in trunked systems.

The traffic intensity offered by each user is equal to the call request rate multiplied by the holding time. That is, each user generates a traffic intensity of Erlangs given by

$$= \lambda H \quad (2.13)$$

where H is the average duration of a call and λ is the average number of call requests per unit time. For a system containing U users and an unspecified number of channels, the total offered traffic intensity A , is given as

$$A = \lambda U H \quad (2.14)$$

46 Ch. 2 • The Cellular Concept — System Design Fundamentals Table 2.3 Definitions of Common Terms Used In Trunking Theory

Set-up Time: The time required to allocate a trunked radio channel to a requesting user. **Blocked Call:** Call which cannot be completed at time of request, due to congestion. Also referred to as a lost call.

Holding Time: Average duration of a typical call. Denoted by H (in seconds).
 Traffic Intensity: Measure of channel time utilization, which is the average channel occupancy measured in Erlangs. This is a dimensionless quantity and may be used to measure the time utilization of single or multiple channels. Denoted by A .
 Load: Traffic intensity across the entire trunked radio system, measured in Erlangs.
 Grade of Service (GOS): A measure of congestion which is specified as the probability of a call being blocked (for Erlang B), or the probability of a call being delayed beyond a certain amount of time (for Erlang C).
 Request Rate: The average number of call requests per unit time. Denoted by λ .

Furthermore, in a C channel trunked system, if the traffic is equally distributed among the channels, then the traffic intensity per channel, is given as

$$= \frac{A}{C} \quad (2.15)$$

Note that the offered traffic is not necessarily the traffic which is carried by the trunked system, only that which is offered to the trunked system. When the offered traffic exceeds the maximum capacity of the system, the carried traffic becomes limited due to the limited capacity (i.e. limited number of channels).

The maximum possible carried traffic is the total number of channels, C , in Erlangs. The AMPS cellular system is designed for a GOS of 2% blocking. This implies that the channel allocations for cell sites are designed so that 2 out of 100 calls will be blocked due to channel occupancy during the busiest hour.

There are two types of trunked systems which are commonly used. The first type offers no queuing for call requests. That is, for every user who requests service, it is assumed there is no setup time and the user is given immediate access to a channel if one is available. If no channels are available, the requesting user is blocked without access and is free to try again later. This type of trunking is called blocked calls cleared and assumes that calls arrive as determined by a Poisson distribution. Furthermore, it is assumed that there are an infinite number of users as well as the following: (a) there are memoryless arrivals of requests, implying that all users, including blocked users, may request a channel at any time; (b) the probability of a user occupying a channel is exponentially distributed, so that longer calls are less likely to occur as described by an exponential distribution; and (c) there are a finite number of channels available in the trunking pool. This is known as an M/M/1 queue, and leads to the derivation of the Erlang B formula (also known as the blocked calls cleared formula). The Erlang B formula determines the probability that a call is blocked and is a measure of the GOS for a trunked system which provides no queuing for blocked calls. The Erlang B formula is derived in Appendix A and is given by

AC

$$\Pr[\text{blocking}] = \text{GOS} \quad (2.16)$$

k = 0

where C is the number of trunked channels offered by a trunked radio system and A is the total offered traffic. While it is possible to model trunked systems with finite users, the resulting expressions are much more complicated than the Erlang B result, and the added complexity is not warranted for typical trunk systems which have users that outnumber available channels by orders of magnitude. Furthermore, the Erlang B formula provides a conservative estimate of the GOS, as the finite user results always predict a smaller likelihood of blocking. The capacity of a trunked radio system where blocked calls are lost is tabulated for various values of GOS and numbers of channels in Table 2.4.

Table 2.4 Capacity of an Erlang B System
Capacity (Erlangs) for GOS

Number of
Channels C

= 0.01 = 0.005 = 0.002 = 0.001

2 0.153 0.105 0.065 0.046

4 0.869 0.701 0.535 0.439

5 1.36 1.13 0.900 0.762

10 4.46 3.96 3.43 3.09

20 12.0 11.1 10.1 9.41

24 15.3 14.2 13.0 12.2

40 29.0 27.3 25.7 24.5

70 56.1 53.7 51.0 49.2

100 84.1

80.9 77.4 75.2

The second kind of trunked system is one in which a queue is provided to hold calls which are blocked. If a channel is not available immediately, the call request may be delayed until a channel becomes available. This type of trunking is called Blocked Calls Delayed, and its measure of GOS is defined as the probability that a call is blocked after

waiting a specific length of time in the **queue.** To find the GOS, it is first necessary

to find the likelihood that a call is initially denied access to the system. The likelihood of

a call not having immediate access to a channel is determined by the Erlang C formula derived in Appendix A

$$\Pr[\text{delay} > 0] = \quad (2.17)$$

48 Ch. 2 • The Cellular Concept — System Design Fundamentals If no channels are immediately available the call is delayed, and the probability that the delayed call is forced to wait more than t seconds is given by the probability that a call is delayed, multiplied by the conditional probability that the delay is greater than t seconds. The GOS of a trunked

system where blocked calls are delayed is hence given by

$$Pr[\text{delay} > t] = Pr[\text{delay} > 0 | Pr[\text{delay} > 0 | \text{delay} > 0]] \quad (2.18) = Pr[\text{delay} > 0] \exp(-(C-A)t/H)$$

The average delay D for all calls in a queued system is given by

$$D = Pr[\text{delay} > 0] j' A \quad (2.19)$$

where the average delay for those calls which are queued is given by $H/(C-A)$. The Erlang B and Erlang C formulas are plotted in graphical form in Figure 2.6 and Figure 2.7. These graphs are useful for determining GOS in rapid fashion, although computer simulations are often used to determine transient behaviors experienced by particular users in a mobile system. To use Figure 2.6 and Figure 2.7, locate the number of channels on the top portion of the graph. Locate the traffic intensity of the system on the bottom portion of the graph. The blocking probability $Pr[\text{blocking}]$ is shown on the abscissa of Figure 2.6, and $Pr[\text{delay} > 0]$ is shown on the abscissa of Figure 2.7. With two of the parameters specified it is easy to find the third parameter.

Example 2.4

How many users can be supported for 0.5% blocking probability for the following number of trunked channels in a blocked calls cleared system? (a) 1, (b) 5, (c) 10, (d) 20, (e) 100. Assume each user generates 0.1 Erlangs of traffic.

Solution to Example 2.4

From Table 2.4 we can find the total capacity in Erlangs for the 0.5% GOS for different numbers of channels. By using the relation $A = UAU$, we can obtain the total number of users that can be supported in the system. (a) Given $C = 1, AU = 0.1, \text{GOS} = 0.005$

From Figure 2.6, we obtain $A = 0.005$.

Therefore, total number of users, $U = A/AU = 0.005/0.1 = 0.05$ users. But, actually one user could be supported on one channel. So, $U = 1$. (b) Given $C = 5, AU = 0.1, \text{GOS} = 0.005$

From Figure 2.6, we obtain $A = 1.13$.

Therefore, total number of users, $U = A/AU = 1.13/0.1 = 11.3$ users.

(c) Given $C = 10, AU = 0.1, \text{GOS} = 0.005$

From Figure 2.6, we obtain $A = 3.96$.

Therefore, total number of users, $U = A/AU = 3.96/0.1 = 39.6$ users.

(d) Given $C = 20, AU = 0.1, \text{GOS} = 0.005$

From Figure 2.6, we obtain $A = 11.10$.

Therefore, total number of users, $U = A/AU = 11.1/0.1 = 111$ users. (e) Given $C = 100, AU = 0.1, \text{GOS} = 0.005$

12

\$

s

(c)

1

5

Number of Trunked Channels

2

0.1 0.05 0.02

0.01

.4

.0

a

The Erlang B chart showing the probability of blocking as functions of the number of

1

channels and traffic intensity in Erlangs. 00.0

10.0

Traffic Intensity in Erlangs

1.0

0.1

0.001

Figure 2.6

a^{co}

delayed as a function of the number of channels and traffic intensity in Erlangs.

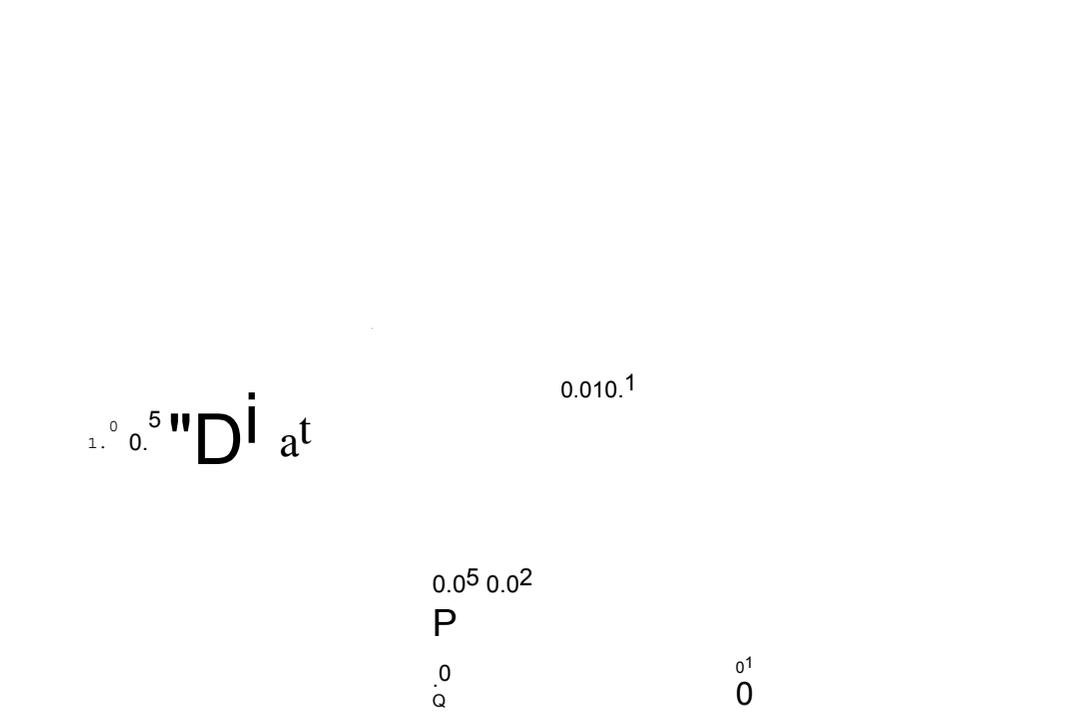
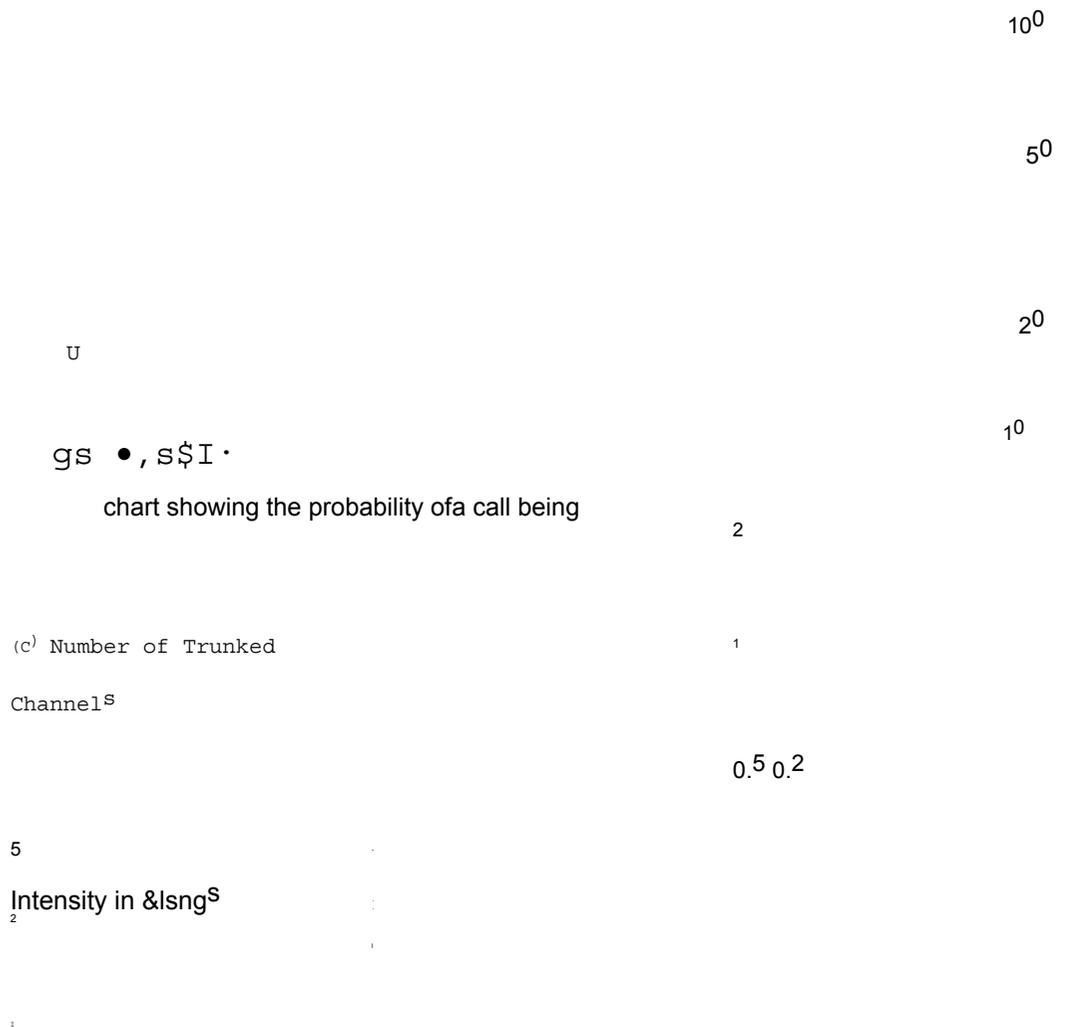


Figure 2.7 The Erlang C Trunking and Grade of Service 51

From Figure 2.6, we obtain $A = 80.9$.

Therefore, total number of users, $U = A/AU = 80.9/0.1 = 809$ users.

Example 2.5

An urban area has a population of 2 million residents. Three competing trunked mobile networks (systems A, B, and C) provide cellular service in this area. System A has 394 cells with 19 channels each, system B has 98 cells with 57 channels each, and system C has 49 cells, each with 100 channels. Find the number of users that can be supported at 2% blocking if each user averages 2 calls per hour at an average call duration of 3 minutes. Assuming that all three trunked systems are operated at maximum capacity, compute the percentage market penetration of each cellular provider.

Solution to Example 2.5

System A

Given:

Probability of blocking = 2% = 0.02

Number of channels per cell used in the system, $C = 19$

Traffic intensity per user, $A_u = \lambda H = 2 \times (3/60) = 0.1$ Erlangs

For $GOS = 0.02$ and $C = 19$, from the Erlang B chart, the total carried traffic, A , is obtained as 12 Erlangs.

Therefore, the number of users that can be supported per cell is

$$U = A/A_u = 12/0.1 = 120.$$

Since there are 394 cells, the total number of subscribers that can be supported by System A is equal to $120 \times 394 = 47280$. System B

Given:

Probability of blocking = 2% = 0.02

Number of channels per cell used in the system, $C = 57$

Traffic intensity per user, $A_u = \lambda H = 2 \times (3/60) = 0.1$ Erlangs

For $GOS = 0.02$ and $C = 57$, from the Erlang B chart, the total carried traffic, A , is obtained as 45 Erlangs. Therefore, the number of users that can be supported per cell is

$$U = A/A_u = 45/0.1 = 450.$$

Since there are 98 cells, the total number of subscribers that can be supported by System B is equal to $450 \times 98 = 44100$. System C

Given:

Probability of blocking = 2% = 0.02

Number of channels per cell used in the system, $C = 100$

Traffic intensity per user, $A_u = \lambda H = 2 \times (3/60) = 0.1$ Erlangs

For $GOS = 0.02$ and $C = 100$, from the Erlang B chart, the total carried traffic, A , is obtained as 88 Erlangs. Therefore, the number of users that can be supported per cell is

$$U = A/A_u = 88/0.1 = 880.$$

Since there are 49 cells, the total number of subscribers that can be supported by System C is equal to $880 \times 49 = 43120$
 Therefore, total number of cellular subscribers that can be supported by these three systems are $47280 + 44100 + 43120 = 134500$ users.

Since there are 2 million residents in the given urban area and the total number of cellular subscribers in System A is equal to 47280, the percentage market penetration is equal to

$$47280/2000000 = 2.36\%$$

Similarly, market penetration of System B is equal to

$$44100/2000000 = 2.205\%$$

and the market penetration of System C is equal to

$$43120/2000000 = 2.156\%$$

The market penetration of the three systems combined is equal to

$$134500/2000000 = 6.725\%$$

Example 2.6

A certain city has an area of 1,300 square miles and is covered by a cellular system using a 7-cell reuse pattern. Each cell has a radius of 4 miles and the city is allocated 40 MHz of spectrum with a full duplex channel bandwidth of 60 kHz. Assume a GOS of 2% for an Erlang B system is specified. If the offered traffic per user is 0.03 Erlangs, compute (a) the number of cells in the service area, (b) the number of channels per cell, (c) traffic intensity of each cell, (d) the maximum carried traffic; (e) the total number of users that can be served for 2% GOS, (f) the number of mobiles per channel, and (g) the theoretical maximum number of users that could be served at one time by the system.

Solution to Example 2.6

(a) Given:

Total coverage area = 1300 miles

Cell radius = 4 miles

The area of a cell (hexagon) can be shown to be $2.5981R^2$, thus each cell covers

$$2.5981 \times (4)^2 = 41.57 \text{ sqmi.}$$

Hence, the total number of cells are = $1300/41.57 = 31$ cells.

(b) The total number of channels per cell (C)

$$= \text{allocated spectrum} / (\text{channel width} \times \text{frequency reuse factor}) \\ = 40,000,000 / (60,000 \times 7) = 95 \text{ channels/cell}$$

(c) Given:

$C = 95$, and $GOS = 0.02$

From the Erlang B chart, we have

traffic intensity per cell $A = 84$ Erlangs/cell

(d) Maximum carried traffic = number of cells \times traffic intensity per cell
 $= 31 \times 84 = 2604$ Erlangs.

(e) Given traffic per user = 0.03 Erlangs

Total number of users = Total traffic / traffic per user

$$= 2604 / 0.03 = 86,800 \text{ users.}$$

(f) Number of mobiles per channel = number of users/number of channels = $86,800 / 666 = 130$ mobiles/channel.

(g) The theoretical maximum number of served mobiles is the number of available channels in the system (all channels occupied)

$$= C \times N_c = 95 \times 31 = 2945 \text{ users, which is } 3.4\% \text{ of the customer base.}$$

Example 2.7

A hexagonal cell within a 4-cell system has a radius of 1.387 km. A total of 60 channels are used within the entire system. If the load per user is 0.029 Erlangs, and $X =$ call/hour, compute the following for an Erlang C system that has a 5% probability of a delayed call:

- (a) How many users per square kilometer will this system support? (a) What is the probability that a delayed call will have to wait for more than 10s?
 (c) What is the probability that a call will be delayed for more than 10 seconds?

Solution to Example 2.7

Given,

Cell radius, $R = 1.387$ km

Area covered per cell is $2.598 \times (1.387)^2 = 5$ sq km

Number of cells per cluster = 4

Total number of channels = 60

Therefore, number of channels per cell = $60 / 4 = 15$ channels.

- (a) From Erlang C chart, for 5% probability of delay with $C = 15$, traffic intensity = 9.0 Erlangs.

Therefore, number of users = total traffic intensity / traffic per user
 $= 9.0 / 0.029 = 310$ users
 $= 310 \text{ users} / 5 \text{ sq km} = 62 \text{ users/sq km}$

- (b) Given $1. = \text{holding time}$

$H = A_s/A = 0.029 \text{ hour} = 104.4 \text{ seconds.}$

The probability that a delayed call will have to wait for more than 10 s is

$$\Pr[\text{delay} > t] = \exp(-(C-A)t/H) = \exp(-(15-9.0)(10/104.4)) = 56.29 \%$$

- (c) Given $\Pr[\text{delay} > 0] = 5\% = 0.05$

Probability that a call is delayed more than 10 seconds,

$$\Pr\{\text{delay} > t\} = 0.05 \times 0.5629 = 2.81 \%$$

Trunking efficiency is a measure of the number of users which can be offered a particular GOS with a particular configuration of fixed channels. The way in which channels are grouped can substantially alter the number of users handled by a trunked system. For example, from Table 2.4, 10 trunked channels at a GOS of 0.01 can support

groups of 5

4.46 Erlangs of traffic, whereas 2 trunked channels can support 2 x

1.36 Erlangs, or 2.72 Erlangs of traffic.

Clearly, 10 channels trunked together support 60% more traffic at a specific GOS than do two 5 channel trunks! It should be clear that the allocation of channels in a trunked radio system has a major impact on overall system capacity.

2.7 Improving Capacity In Cellular Systems

As the demand for wireless service increases, the number of channels assigned to a cell eventually becomes insufficient to support the required number of users. At this point, cellular design techniques are needed to provide more channels per unit coverage area. Techniques such as cell splitting, sectoring, and coverage zone approaches are used in practice to expand the capacity of cellular systems. Cell splitting allows an orderly growth of the cellular system. Sectoring uses directional antennas to further control the interference and frequency reuse of channels. The zone microcell concept distributes the coverage of a cell and extends the cell boundary to hard-to-reach places. While cell splitting increases the number of base stations in order to increase capacity, sectoring and zone microcells rely on base station antenna placements to improve capacity by reducing co-channel interference. Cell splitting and zone microcell techniques do not suffer the trunking inefficiencies experienced by sectored cells, and enable the base station to oversee all handoff chores related to the microcells, thus reducing the computational load at the MSC. These three popular capacity improvement techniques will be explained in detail.

2.7.1 Cell Splitting

Cell splitting is the process of subdividing a congested cell into smaller cells, each with its own base station and a corresponding reduction in antenna height and transmitter power. Cell splitting increases the capacity of a cellular system since it increases the number of times that channels are reused. By defining n^* cells which have a smaller radius than the original cells and by installing these smaller cells (called microcells) between the existing cells, capacity increases due to the additional number of channels per unit area.

Imagine if every cell in Figure 2.1 were reduced in such a way that the radius of every cell was cut in half. In order to cover the entire service area with smaller cells, approximately four times as many cells would be required. This can be easily shown by considering a circle with radius R . The area covered by such a circle is four times as large as the area covered by a circle with radius $R/2$. The increased number of cells would increase the number of clusters over the coverage region, which in turn would increase the number of channels, and thus capacity, in the coverage area. Cell splitting allows a system to grow by replacing large cells with smaller cells, while not upsetting the channel allocation scheme required to maintain the minimum co-channel reuse ratio Q (see equation (2.4)) between co-channel cells.

Improving Capacity in Cellular Systems 55

An example of cell splitting is shown in Figure 2.8. In Figure 2.8, the base stations are placed at corners of the cells, and the area served by base station A is assumed to be saturated with traffic (i.e., the blocking of base station A exceeds acceptable rates). New base stations are therefore needed in the region to increase the number of channels in the area and to reduce the area served by the single base station. Note in the figure that the original base station A has been surrounded by six new microcell base stations. In the example

shown in Figure 2.8, the smaller cells were added in such a way as to preserve the frequency reuse plan of the system. For example, the microcell base station labeled G was placed half way between two larger stations utilizing the same channel set G. This is also the case for the other microcells in the figure. As can be seen from Figure 2.8, cell splitting merely scales the geometry of the cluster. In this case, the radius of each new microcell is half that of the original cell.

C

D

F

E

F

Figure 2.8
Illustration of cell splitting.

For the new cells to be smaller in size, the transmit power of these cells must be reduced. The transmit power of the new cells with radius half that of the original cells can be found by examining the received power at the new and old cell boundaries and setting them equal to each other. This is necessary to ensure that the frequency reuse plan for the new microcells behaves exactly as for the original cell's. For Figure 2.8

at old cell boundary] $P_1 \propto (2.20)$
and

at new cell boundary] $P_2 \propto P_1 (R/2)^{2n}$ (2.21)

where P_1 and P_2 are the transmit powers of the larger and smaller cell base stations, respectively, and n is the path loss exponent. If we take $n = 4$ and set the received powers equal to each other, then

$$P_2 = P_1 / 16 \quad (2.22)$$

In other words, the transmit power must be reduced by 12 dB in order to fill in the

original coverage area with microcells, while maintaining the S/I requirement.

In practice, not all cells are split at the same time. It is often difficult for service providers to find real estate that is perfectly situated for cell splitting. Therefore, different cell sizes will exist simultaneously. In such situations, special care needs to be taken to keep the distance between co-channel cells at the required minimum, and hence channel assignments become more complicated [Rap97]. Also, handoff issues must be addressed so that high speed and low speed traffic can be simultaneously accommodated (the umbrella cell approach of Section 2.4 is commonly used). When there are two cell sizes in the same region as shown in Figure 2.8, equation (2.22) shows that one can not simply use the original transmit power for all new cells or the new transmit power for all the original cells. If the larger transmit power is used for all cells, some channels used by the smaller cells would not be sufficiently separated from co-channel cells. On the other hand, if the smaller transmit power is used for all the cells, there would be parts of the larger cells left unserved. For this reason, channels in the old cell must be broken down into two channel groups, one that corresponds to the smaller cell reuse requirements and the other that corresponds to the larger cell reuse requirements. The larger cell is usually dedicated to high speed traffic so that handoffs occur less frequently.

The two channel group sizes depend on the stage of the splitting process. At the beginning of the cell splitting process there will be fewer channels in the small power groups. However, as demand grows, more channels will be required, and thus the smaller groups will require more channels. This splitting process continues until all the channels in an area are used in the lower power group, at which point cell splitting is complete within the region, and the entire system is rescaled to have a smaller radius per cell. Antenna downtilting, which deliberately focuses radiated energy from the base station towards the ground (rather than towards the horizon), is often used to limit the radio coverage of newly formed microcells.

Example 2.8

Consider Figure 2.9. Assume each base station uses 60 channels, regardless of cell size. If each original cell has a radius of 1 km and each microcell has a radius of 0.5 km, find the number of channels contained in a 3 km by 3 km

Improving Capacity in Cellular Systems 57

square centered around A, (a) without the use of microcells, (b) when the lettered microcells as shown in Figure 2.9 are used, and (c) if all the original base stations are replaced by microcells. Assume cells on the edge of the square to be contained within the square.

Solution to Example 2.8

(a) without the use of microcells:

A cell radius of 1 km implies that the sides of the larger hexagons are also 1 km in length. To cover the 3 km by 3 km square centered around base station A, we need to cover 1.5 km (1.5 times the hexagon radius) towards the right, left, top, and bottom of base station A. This is shown in Figure 2.9.

From Figure 2.9 we see that this area contains 5 base stations. Since each base station has 60 channels, the total number of channels without cell splitting is

equal to $5 \times 60 = 300$ channels.

(b) with the use of the microcells as shown in Figure 2.9:

In Figure 2.9, the base station A is surrounded by 6 microcells. Therefore, the total number of base stations in the square area under study is equal to $5 + 6 = 11$. Since each base station has 60 channels, the total number of channels will be equal to $11 \times 60 = 660$ channels. This is a 2.2 times increase in capacity when compared to case (a).

(c) if all the base stations are replaced by microcells:

From Figure 2.9, we see that there are a total of $5 + 12 = 17$ base stations in the square region under study. Since each base station has 60 channels, the total number of channels will be equal to $17 \times 60 = 1020$ channels. This is

a 3.4 times increase in capacity when compared to case (a).

Theoretically, if all cells were microcells having half the radius of the original cell, the capacity increase would approach 4.

2.7.2 Sectoring

As shown in section 2.7.1, cell splitting achieves capacity improvement by essentially rescaling the system. By decreasing the cell radius R and keeping the co-channel reuse ratio D/R unchanged, cell splitting increases the number of channels per unit area. However, another way to increase capacity is to keep the cell radius unchanged and seek methods to decrease the D/R ratio. In this approach, capacity improvement is achieved by reducing the number of cells in a cluster and thus increasing the frequency reuse. However, in order to do this, it is necessary to reduce the relative interference without decreasing the transmit power.

The co-channel interference in a cellular system may be decreased by replacing a single omni-directional antenna at the base station by several directional antennas, each radiating within a specified sector. By using directional antennas, a given cell will receive interference and transmit with only a fraction

F

Figure 2.9
illustration of cell splitting within a 3 km by 3 km square centered around base station A.

of the available co-channel cells. The technique for decreasing co-channel interference and thus increasing system capacity by using directional antennas is called sectoring. The factor by which the co-channel interference is reduced depends on the amount of sectoring used. A cell is normally partitioned into three 120° sectors or six 60° sectors as shown in Figure 2.10(a) and (b).

When sectoring is employed, the channels used in a particular cell are broken down into sectorized groups and are used only within a particular sector, as illustrated in Figure 2.10(a) and (b). Assuming 7-cell reuse, for the case of 120° sectors, the number of interferers in the first tier is reduced from 6 to 2. This is because only 2 of the 6 co-channel cells receive interference with a particular sectorized channel group. Referring to Figure 2.11, consider the interference experienced by a mobile located in the right-most sector in the center cell labeled '5'. There are 3 co-channel cell sectors labeled '5' to the right of the center cell, and 3 to the left of the center cell. Out of these 6 co-channel cells, only 2 cells have sectors with antenna patterns which radiate into the center cell, and hence a mobile in the center cell will experience interference on the forward link from only these two sectors. The resulting S/I for this

sectoring. sectoring.

Figure 2.10 (a) 1200 (b)

tion (2.8) to be 24.2 dB, which is a significant improvement over the omni-directional case in Section 2.5, where the worst case S/I was shown to be 17 dB. In practical systems, further improvement in S/I is achieved by downtilting the sector antennas such that the radiation pattern in the vertical (elevation) plane has a notch at the nearest co-channel cell distance.

The improvement in S/I implies that with 1200 sectoring, the minimum required S/I of 18 dB can be easily achieved with 7-cell reuse, as compared to 12-cell reuse for the worst possible situation in the unsectoring case (see Section 2.5.1). Thus, sectoring reduces interference, which amounts to an increase

in capacity by a factor of $12/7$, or 1.714. In practice, the reduction in interference offered by sectoring enables planners to reduce the cluster size N , and provides an additional degree of freedom in assigning channels. The penalty for unproved S/I and the resulting capacity improvement is an increased number of antennas at each base station, and a decrease in trunking efficiency due to channel sectoring at the base station. Since sectoring reduces the coverage area of a particular group of

channels, the number of handoffs increases, as well. Fortunately, many modern base stations support sectorization and allow mobiles to be handed off from sector to sector within the same cell without intervention from the MSC, so the handoff problem is often not a major concern. It is the loss of traffic due to decreased trunking efficiency

causes some

that operators to shy away from the sectoring approach, particularly in dense urban areas where the directional antenna patterns are somewhat ineffective in controlling radio propagation. Because sectoring uses more than one antenna per base station, the available channels in the cell must be subdivided and dedicated

Figure 2.11

Illustration of how 120° sectoring reduces interference from co-channel cells. Out of the 6 co-channel cells in the first tier, only 2 of them interfere with the center cell. If omni-directional antennas were used at each base station, all 6 co-channel cells would interfere with the center cell.

to a specific antenna. This breaks up the available trunked channel pool into several smaller pools, and decreases trunking efficiency.

Example 2.9

Consider a cellular system in which an average call lasts 2 minutes, and the probability of blocking is to be no more than 1%. Assume that every subscriber makes 1 call per hour, on average. If there are a total of 395 traffic channels for a 7-cell reuse system, there will be about 57 traffic channels per cell. Assume that blocked calls are cleared so the blocking is described by the Erlang B distribution. From the Erlang B distribution, it can be found that the unsectorized system may handle 44.2 Erlangs or 1326 calls per hour.

Now employing 120° sectoring, there are only 19 channels per antenna sector (57/3 antennas). For the same probability of blocking and average call length, it can be found from the Erlang B distribution that each sector can handle 11.2

Improving Capacity in Cellular Systems 61

Erlangs or 336 calls per hour. Since each cell consists of 3 sectors, this provides a cell capacity of $3 \times 336 = 1008$ calls per hour, which amounts to a 24% decrease when compared to the unsectorized case. Thus, sectoring decreases the trunking efficiency while improving the S/I for each user in the system.

it can be found that using 60° sectors improves the S/I even more. in this case the number of first tier iriterferers is reduced from 6 to only 1. This results in $S/I = 29\text{dB}$ for a 7-cell system and enables 4-cell reuse. Of course, using 6 sec tors per cell reduces the trunking efficiency and increases the number of neces sary handofis even more. If the unsectored system is compared to the 6 sector case, the degradation in trunking efficiency can be shown to be 44%. (The proof of this is left as an exercise).

2.7.3 A Novel Microcell Zone Concept

The increased number of handoffs required when sectoring is employed results in an increased load on the switching and control link elements of the mobile system. A solution to this problem was presented by Lee [Lee91b]. This proposal is based on a microcell concept for 7 cell reuse, as illustrated in Figure 2.12. In this scheme, each of the three (or possibly more) zone sites (represented as Tx/Rx in Figure 2.12) are connected to a single base station and share the same radio equipment. The zones are connected by coaxial cable, fiberoptic cable, or microwave link to the base station. Multiple zones and a single base station make up a cell. As a mobile travels within the cell, it is served by the zone with the strongest signal. This approach is superior to sectoring since antennas are placed at the outer edges of the cell, and any base station channel may be assigned to any zone by the base station.

As a mobile travels from one zone to another within the cell, it retains the same channel. Thus, unlike in sectoring, a handoff is not required at the MSC when the mobile travels between zones within the cell. The base station simply switches the channel to a different zone site. In this way, a given channel is active only in the particular zone in which the mobile is traveling, and hence the base station radiation is localized and interference is reduced. The channels are distributed in time and space by all three zones and are also reused in co-channel cells in the normal fashion. This technique is particularly useful along high ways or along urban traffic corridors.

The advantage of the zone cell technique is that while the cell maintains a particular coverage radius, the co-channel interference in the cellular system is reduced since a large central base station is replaced by several lower powered transmitters (zone transmitters) on the edges of the cell. Decreased co-channel interference improves the signal quality and also leads to an increase in capacity, without the degradation in trunking efficiency caused by sectoring. As mentioned earlier, an S/I of 18 dB is typically required for satisfactory system performance in narrowband FM. For a system with $N = 7$, a D/R of 4.6 was

Figure 2.12

The microcell concept [adapted from (Lee91b) © IEEE].

shown to achieve this. With respect to the zone microcell system, since transmission at any instant is confined to a particular zone, this implies that a DZ/RZ of 4.6 (where D is the minimum distance between active co-channel zones and R is the zone radius) can achieve the required link performance. In Figure 2.13, let each individual hexagon represent a zone, while each group of three hexagons represents a cell. The zone radius is approximately equal to one hexagon radius. Now, the capacity of the zone microcell system is directly related to the distance between co-channel cells, and not zones. This distance is represented as D in Figure 2.13. For a value of 4.6, it can be seen from the geometry of Figure 2.13 that the value of co-channel reuse ratio, D/R , is equal to 3, where R is the radius of the cell and is equal to twice the length of the hexagon radius. Using equation (2.4), $D/R = 3$ corresponds to a cluster size of $N = 3$. This reduction in the cluster size from $N = 7$ to $N = 3$ amounts to a 2.33 times increase in capacity for a system completely based on the zone microcell concept. Hence for the same S/I requirement of 18 dB, this system provides a significant increase in capacity over conventional cellular planning.

Summary 63

By examining Figure 2.13 and using equation (2.8) [Lee91b] the exact worst case S/I of the zone microcell system can be estimated to be 20 dB. Thus, in the worst case, the system provides a margin of 2 dB over the required signal-to-interference ratio while increasing the capacity by 2.33 times over a conventional 7-cell system using omnidirectional antennas. No loss in trunking efficiency is experienced. Zone cell

architectures are being adopted in many cellular and personal communication systems.

2.8 Summary

In this chapter, the fundamental concepts of handoff, frequency reuse, trunking efficiency, and frequency planning have been presented. Handoffs are required to pass mobile traffic from cell to cell, and there are various ways handoffs are implemented. The capacity of a cellular system is a function of many variables. The S/I limits the frequency reuse factor of a system, which limits the number of channels within the coverage area. The trunking efficiency limits the number of users that can access a trunked radio system. Trunking is affected by the number of available channels and how they are partitioned in a trunked cellular system. Trunking efficiency is quantified by the GOS. Finally, cell splitting, sectoring, and the zone microcell technique are all shown to improve capacity by increasing S/I in some fashion. The overriding objective in all of these methods is to increase the number of users within the system. The radio propagation characteristics influence the effectiveness of all of these methods in an actual system. Radio propagation is the subject of the following two chapters.

2.9 Problems

2.1 Prove that for a hexagonal geometry, the co-channel reuse ratio is given by $Q = \sqrt{3}N$, where $N = i^2 + j^2$. (Hint: use the cosine law and the hexagonal cell geometry).

2.2 Show that the frequency reuse factor for a cellular system is given by k/S , where k is the average number of channels per cell and S is the total number of channels available to the cellular service provider.

2.3 A cellular service provider decides to use a digital TDMA scheme which can tolerate a signal-to-interference ratio of 15 dB in the worst case. Find the optimal value of N for (a) omni-directional antennas, (b) 120° sectoring, and (c) 60° sectoring. Should sectoring be used? If so, which case (60° or 120°) should be used? (Assume a path loss exponent of $n = 4$ and consider trunking efficiency).

2.4 If an intensive propagation measurement campaign showed that the mobile radio channel provided a propagation path loss exponent of $n = 3$ instead of 4, how would your design decisions in Problem 2.3 change? What is the optimal value of N for the case of $n =$

3?

2.5 For a $N = 7$ system with a $P_{\text{block}} = 1\%$ and average call length of 2 minutes, find the traffic capacity loss due to trunking for 57 channels when going from omni-directional antennas to 60° sectored antennas. (Assume that blocked calls are cleared and the average per user call rate is $X = 1$ per hour.)

Figure 2.13

Defining $D, D_1, I?$, for a microcell architecture with $N = 7$. The smaller hexagons form zones and three hexagons (outlined in bold) together form a cell. Six nearest co-channel cells are shown.

2.6 Assume that a cell named "Radio Knob" has 57 channels, each with an effective radiated power of 32 watts and a cell radius of 10 km. The grade of service is established to be a probability of blocking of 5% (assuming blocked calls are cleared). Assume the average call length is 2 minutes, and each user averages 2 calls per hour. Further, assume the cell has just reached its maximum capacity and must be split into 4 new microcells to provide 4 times the capacity in the same area. (a) What is the current capacity of the "Radio Knob" cell? (b) What is the radius and transmit power of the new cells? (c) How many channels are needed in each of the new cells to maintain frequency reuse stability in the system? (d) If traffic is uniformly distributed, what is the new traffic carried by each new cell? Will the probability of blocking in these new cells be below 0.1% after the split?

2.7 Exercises in trunking (queueing) theory:

- (a) What is the maximum system capacity (total and per channel) in Erlangs when providing a 2% blocking probability with 4 channels, with 20 channels, with 40 channels?
- (b) How many users can be supported with 40 channels at 2% blocking? Assume $H = 105$ s, $A = 1$ call/hour.
- (c) Using the traffic intensity per channel calculated in part (a), find the grade of service in a lost call delayed system for the case of delays being greater than 20 seconds. Assume that $H = 105$ s, and determine the GUS

65 Ch. 2 • The Cellular Concept — System Design Fundamentals

for 4 channels, for 20 channels, for 40 channels.

(d) Comparing part (a) and part (c), does a lost call delayed system with a 20 second queue perform better than a system that clears blocked calls? 2.8 A receiver in an urban

cellular radio system detects a 1 mW signal at $d = r_c$ meter from the transmitter. In order to mitigate co-channel interference effects, it is required that the signal received at any base station receiver from another base station transmitter which operates with the same channel must be below -100 dBm. A measurement team has determined that the average path loss exponent in the system is $n = 3$. Determine the major radius of each cell if a 7-cell reuse pattern is used. What is the major radius if a 4-cell reuse pattern is used?

- 2.9 A cellular system using a cluster size of 7 is described in Problem 2.8. It is operated with 660 channels, 30 of which are designated as setup (control) channels so that there are about 90 voice channels available per cell. If there is a potential user density of 9000 users/km² in the system, and each user makes an average of one call per hour and each call lasts 1 minute during peak hours, determine the probability that a user will experience a delay greater than 20 seconds if all calls are queued.
- 2.10 Show that if $n = 4$, a cell can be split into four smaller cells, each with half the radius and 1/16 of the transmitter power of the original cell. If extensive measurements show that the path loss exponent is 3, how should the transmitter power P be changed in order to split a cell into four smaller cells? What impact will this have on the cellular geometry? Explain your answer and provide drawings that show how the new cells would fit within the original macrocells. For simplicity use omni-directional antennas.
- 2.11 Using the frequency assignment chart in Table 2.2, design a channelization scheme for a B-side carrier that uses 4-cell reuse and 3 sectors per cell. Include an allocation scheme for the 21 control channels.
- 2.12 Repeat Problem 2.11 for the case of 4-cell reuse and 6 sectors per cell.
- 2.13 In practical cellular radio systems, the MSC is programmed to allocate radio channels differently for the closest co-channel cells. This technique, called a hunting sequence, ensures that co-channel cells first use different channels from within the co-channel set, before the same channels are assigned to calls in nearby cells. This minimizes co-channel interference when the cellular system is not fully loaded. Consider 3 adjoining clusters, and design an algorithm that may be used by the MSC to hunt for appropriate channels when requested from co-channel cells. Assume a 7-cell reuse pattern with 3 sectors per cell, and use the U.S. cellular channel allocation scheme for the A-side carrier.
- 2.14 Determine the noise floor (in dBm) for mobile receivers which implement the following standards: (a) AMPS, (b) GSM, (c) USDC, (d) DECT, (e) 18-95, and (f) CT2. Assume all receivers have a noise figure of 10 dB.
- 2.15 If a base station provides a signal level of -90 dBm at the cell fringe, find the SNR for each of the mobile receivers described in Problem 2.14.
- 2.16 From first principles, derive the expression for Erlang B given in this chapter. Carefully analyze the trade-off between sectoring and trunking efficiency for a 4-cell cluster size. While sectoring improves capacity by improving SNR, there is a loss due to decreased trunking efficiency, since each sector must be trunked separately. Consider a wide range of total available channels per cell and consider the impact of using 3 sectors and 6 sectors per cell. Your analysis may involve computer simulation, and should indicate the "break even" point when

66 Gb. 2 • The Cellular Concept — System Design Fundamentals

sectoring is not practical.

2.18 Assume each user of a single base station mobile radio system averages three calls per hour, each call lasting an average of 5 minutes.

- What is the traffic intensity for each user?
- Find the number of users that could use the system with 1% blocking if only one channel is available.
- Find the number of users that could use the system with 1% blocking if

five trunked channels are available.

(d) If the number of users you found in (c) is suddenly doubled, what is the new blocking probability of the five channel trunked mobile radio system? Would this be acceptable performance? Justify why or why not.

2.19 The U.S. AMPS system is allocated 50 MHz of spectrum in the 800 MHz range, and provides 832 channels. Forty-two of those channels are control channels. The forward channel frequency is exactly 45 MHz greater than the reverse channel frequency.

(a) Is the AMPS system simplex, half-duplex, or duplex? What is

the bandwidth for each channel and how is it distributed between the base station and the subscriber?

(b) Assume a base station transmits control information on channel 352, operating at 880.560 MHz. What is the transmission frequency of a subscriber unit transmitting on channel 352?

(c) The A-side and B-side cellular carriers evenly split the AMPS channels. Find the number of voice channels and number of control channels for each carrier.

(d) Let's suppose you are chief engineer of a cellular carrier using 7-cell reuse. Propose a channel assignment strategy for a uniform distribution of users throughout your cellular system. Specifically, assume that each cell has 3 control channels (1200 sectoring is employed) and specify the number of voice channels you would assign to each control channel in your system.

(e) For an ideal hexagonal cellular layout which has identical cell sites, what is the distance between the centers of two nearest co-channel cells for 7-cell reuse? for 4-cell reuse?

2.20 Pretend your company won a license to build a U.S. cellular system (the application cost for the license was only \$500!). Your license is to cover 140 square km. Assume a base station costs \$500,000 and a MTSO costs \$1,500,000. An extra \$500,000 is needed to advertise and start the business. You have convinced the bank to loan you \$6 million, with the idea that in four years you will have earned \$10 million in gross billing revenues, and will have paid off the loan.

(a) How many base stations (i.e. cell sites) will you be able to install for \$6 million?

(b) Assuming the earth is flat and subscribers are uniformly distributed on the ground, what assumption can you make about the coverage area of each of your cell sites? What is the major radius of each of your cells, assuming a hexagonal mosaic?

(c) Assume that the average customer will pay \$50 per month over a 4 year period. Assume that on the first day you turn your system on, you have a certain number of customers which remains fixed throughout the year. On the first day of each new year the number of customers using your system

67 Ch. 2 • The Cellular Concept — System Design Fundamentals

doubles and then remains fixed for the rest of that year. What is the minimum number of customers you must have on the first day of service in order to have earned \$10 million in gross billing revenues by the end of the 4th year of operation?

(d) For your answer in (c), how many users per square km are needed on the first day of service in order to reach the \$10 million mark after the 4th

year?