

Wireless Communications

PRINCIPLES AND PRACTICE

Second Edition



THEODORE S. RAPPAPORT

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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 techno-political aspects of cellular radio and personal communications, 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 widespread 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 [Nob62], [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 nontelephone mobile radio applications, such as paging, amateur radio, dispatch, citizens band (CB), public service, cordless phones, or terrestrial microwave radio systems. In fact, in 1990, licensed noncellular radio systems in the U.S. had over 12 million users, more than twice the U.S. cellular user population at that time [FCC91]. With the phenomenal growth of wireless subscribers in the late 1990s, combined with Nextel’s novel business approach of purchasing private mobile radio licenses for bundling as a nationwide commercial cellular service, today’s subscriber base for cellular and *Personal Communication Services* (PCS) far outnumbers all noncellular licensed users. Figure 1.1 shows that the first 35 years of mobile telephony saw little market penetration due to high cost and the technological challenges involved, but how, in the past decade, wireless communications has been accepted by consumers at rates comparable to television and the video cassette recorder.

By 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 5,000 radios were installed in mobiles 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 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

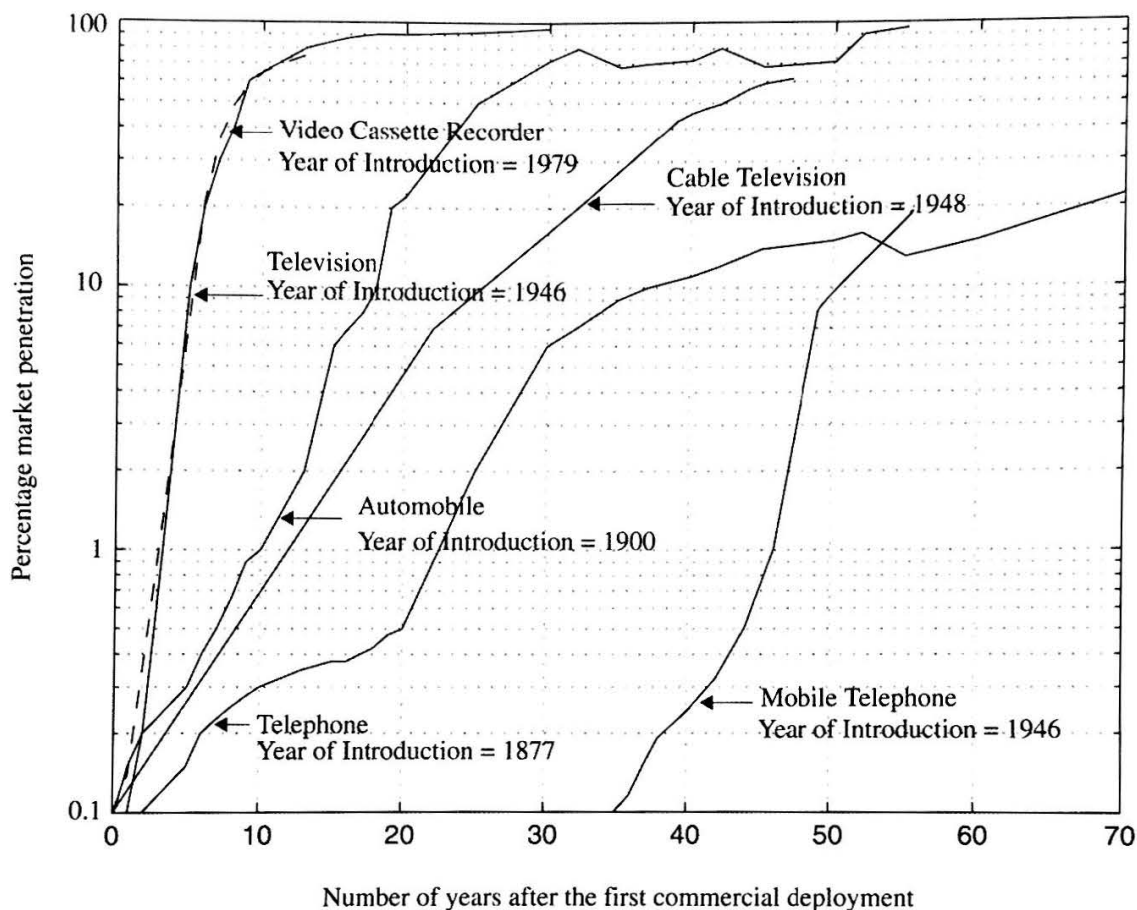


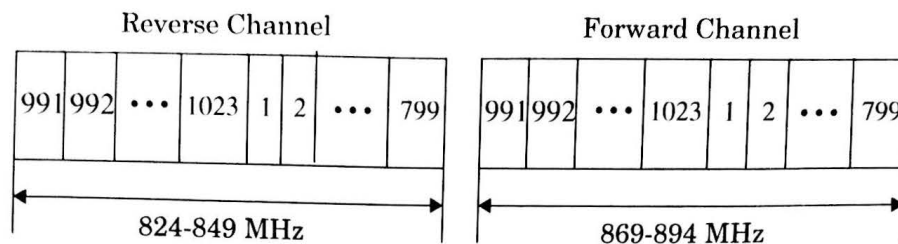
Figure 1.1 The growth of mobile telephony as compared with other popular inventions of the 20th century.

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. [Rap91c], and this number is estimated to be over 100 million as of late 2001. The number of worldwide cellular telephone users grew from 25,000 in 1984 to about 25 million in 1993 [Kuc91], [Goo91], [ITU94], and since then subscription-based wireless services have been experiencing customer growth rates well in excess of 50% per year. As shown in Chapter 2, the worldwide subscriber base of cellular and PCS subscribers is approximately 630 million as of late 2001, compared with approximately 1 billion wired telephone lines. In the first few years of the 21st century, it is clear there will be an equal number of wireless and conventional wireline customers throughout the world! At the beginning of the 21st century, over 1% of the worldwide wireless subscriber population had already abandoned wired telephone service for home use, and had begun to rely solely on their cellular service provider for telephone access. Consumers are expected to increasingly use wireless service as their sole telephone access method in the years to come.

1.2 Mobile Radiotelephony 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 3 kHz of base-band 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 four increase in spectrum efficiency due to technology advances from WWII 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 [Cal88]. However, IMTS quickly became saturated in major markets. By 1976, the Bell Mobile Phone service for the New York City market (a market of about 10,000,000 people at the time) had only twelve channels and could serve only 543 paying customers. There was a waiting list of over 3,700 people [Cal88], 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 re-allocates 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 telephony 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 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 3 and 11, 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



	Channel Number	Center Frequency (MHz)
Reverse Channel	$1 \leq N \leq 799$	$0.030N + 825.0$
	$991 \leq N \leq 1023$	$0.030(N - 1023) + 825.0$
Forward Channel	$1 \leq N \leq 799$	$0.030N + 870.0$
	$991 \leq N \leq 1023$	$0.030(N - 1023) + 870.0$
(Channels 800–990 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.

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.

In late 1991, the first US Digital Cellular (USDC) system hardware was installed in major U.S. cities. The USDC standard (Electronic Industry Association Interim Standard IS-54 and later IS-136) allowed cellular operators to replace gracefully some single-user analog channels with digital channels which support three users in the same 30 kHz bandwidth [EIA90]. In this way, U.S. carriers gradually phased out AMPS as more users accepted digital phones. As discussed in Chapters 9 and 11, the capacity improvement offered by USDC is three times that of AMPS, because digital modulation ($\pi/4$ 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, speech coding technology will increase the capacity to six users per channel in the same 30 kHz bandwidth within a few years, although Chapter 2 demonstrates how IS-136 will eventually be replaced by wideband CDMA technology.

A cellular system based on code division multiple access (CDMA) was developed by Qualcomm, Inc. and standardized by the Telecommunications Industry Association (TIA) as an Interim Standard (IS-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 (SNR) 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 [Gil91]. 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 service providers throughout the country, Nextel and Motorola formed an extended SMR (E-SMR) network in the 800 MHz band that provides capacity and services similar to cellular. Using Motorola's integrated radio system (MIRS), SMR integrates voice dispatch, cellular phone service, messaging, and data transmission capabilities on the same network [Fil95]. In 1995, Motorola replaced MIRS with the *integrated digital enhanced network* (iDen).

Personal Communication Service (PCS) licenses in the 1800/1900 MHz band were auctioned by the U.S. Government to wireless providers in early 1995, and these have spawned new wireless services that complement, as well as compete with, cellular and SMR. One of the stipulations of the PCS license was that a majority of the coverage area be operational before the year 2000. Each PCS licensee was able to "build-out" each market well in advance of this deadline. As many as five PCS licenses are allocated for each major U.S. city (see end of Chapter 11).

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. Tables 1.1 through 1.3 list 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 1.4, and are covered in detail in Chapter 11.

The world's most common paging standard is the Post Office Code Standard Advisory Group (POCSAG) [CCI86], [San82]. POCSAG was developed by the British Post Office in the late 1970s and supports binary frequency shift keying (FSK) signaling at 512 bps, 1200 bps, and 2400 bps. New paging systems, such as FLEX, ReFLEX, and ERMES, provide up to 6400 bps transmissions by using 4-level modulation and are currently being deployed throughout the world.

The CT2 and *Digital European Cordless Telephone* (DECT) standards developed in Europe are the two most popular cordless telephone standards throughout Europe and Asia. The CT2 system makes use of microcells which cover small distances, usually less than 100 m, using base stations with antennas mounted on street lights or on sides of buildings. The CT2 system uses battery efficient frequency shift keying along with a 32 kbps adaptive differential pulse code modulation (ADPCM) speech coder for high quality voice transmission. Handoffs between base stations are not supported in CT2, as it is intended to provide short range access to the PSTN. The DECT system accommodates data and voice transmissions for office and business

Table 1.1 Major Mobile Radio Standards in North America

Standard	Type	Year of Introduction	Multiple Access	Frequency Band	Modulation	Channel Bandwidth
AMPS	Cellular	1983	FDMA	824-894 MHz	FM	30 kHz
NAMPS	Cellular	1992	FDMA	824-894 MHz	FM	10 kHz
USDC	Cellular	1991	TDMA	824-894 MHz	$\pi/4$ -DQPSK	30 kHz
CDPD	Cellular	1993	FH/ Packet	824-894 MHz	GMSK	30 kHz
IS-95	Cellular/ PCS	1993	CDMA	824-894 MHz 1.8-2.0 GHz	QPSK/ BPSK	1.25 MHz
GSC	Paging	1970s	Simplex	Several	FSK	12.5 kHz
POCSAG	Paging	1970s	Simplex	Several	FSK	12.5 kHz
FLEX	Paging	1993	Simplex	Several	4-FSK	15 kHz
DCS-1900 (GSM)	PCS	1994	TDMA	1.85-1.99 GHz	GMSK	200 kHz
PACS	Cordless/ PCS	1994	TDMA/ FDMA	1.85-1.99 GHz	$\pi/4$ -DQPSK	300 kHz
MIRS	SMR/PCS	1994	TDMA	Several	16-QAM	25 kHz
IDen	SMR/PCS	1995	TDMA	Several	16-QAM	25 kHz

users. In the U.S., 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 10.

The world's first cellular system was implemented by the Nippon Telephone and Telegraph company (NTT) 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

Table 1.2 Major Mobile Radio Standards in Europe

Standard	Type	Year of Introduction	Multiple Access	Frequency Band	Modulation	Channel Bandwidth
ETACS	Cellular	1985	FDMA	900 MHz	FM	25 kHz
NMT-450	Cellular	1981	FDMA	450-470 MHz	FM	25 kHz
NMT-900	Cellular	1986	FDMA	890-960 MHz	FM	12.5 kHz
GSM	Cellular /PCS	1990	TDMA	890-960 MHz	GMSK	200 kHz
C-450	Cellular	1985	FDMA	450-465 MHz	FM	20 kHz/ 10 kHz
ERMES	Paging	1993	FDMA	Several	4-FSK	25 kHz
CT2	Cordless	1989	FDMA	864-868 MHz	GFSK	100 kHz
DECT	Cordless	1993	TDMA	1880-1900 MHz	GFSK	1.728 MHz
DCS-1800	Cordless /PCS	1993	TDMA	1710-1880 MHz	GMSK	200 kHz

Table 1.3 Major Mobile Radio Standards in Japan

Standard	Type	Year of Introduction	Multiple Access	Frequency Band	Modulation	Channel Bandwidth
JTACS	Cellular	1988	FDMA	860-925 MHz	FM	25 kHz
PDC	Cellular	1993	TDMA	810-1501 MHz	$\pi/4$ -DQPSK	25 kHz
NTT	Cellular	1979	FDMA	400/800 MHz	FM	25 kHz
NTACS	Cellular	1993	FDMA	843-925 MHz	FM	12.5 kHz
NTT	Paging	1979	FDMA	280 MHz	FSK	12.5 kHz
NEC	Paging	1979	FDMA	Several	FSK	10 kHz
PHS	Cordless	1993	TDMA	1895-1907 MHz	$\pi/4$ -DQPSK	300 kHz

(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 to the U.S. AMPS system, except that the smaller bandwidth channels result in a 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 Chapters 2 and 11, the GSM standard has gained worldwide acceptance as the first universal digital cellular system with modern network features extended to each mobile user, and is the leading digital air interface 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 Wireless Communication 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 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

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 channel 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 base station to the mobile.
Full Duplex Systems	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 Systems	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	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.

subscriber and a base station, by providing two simultaneous but separate channels (frequency division duplex, 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 device called 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 telephone, with the added convenience of mobility. Full duplex and half-duplex systems use *transceivers* for radio communication. FDD is used exclusively in analog mobile radio systems and is described in more detail in Chapter 9.

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 to transmit from the 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. 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 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 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

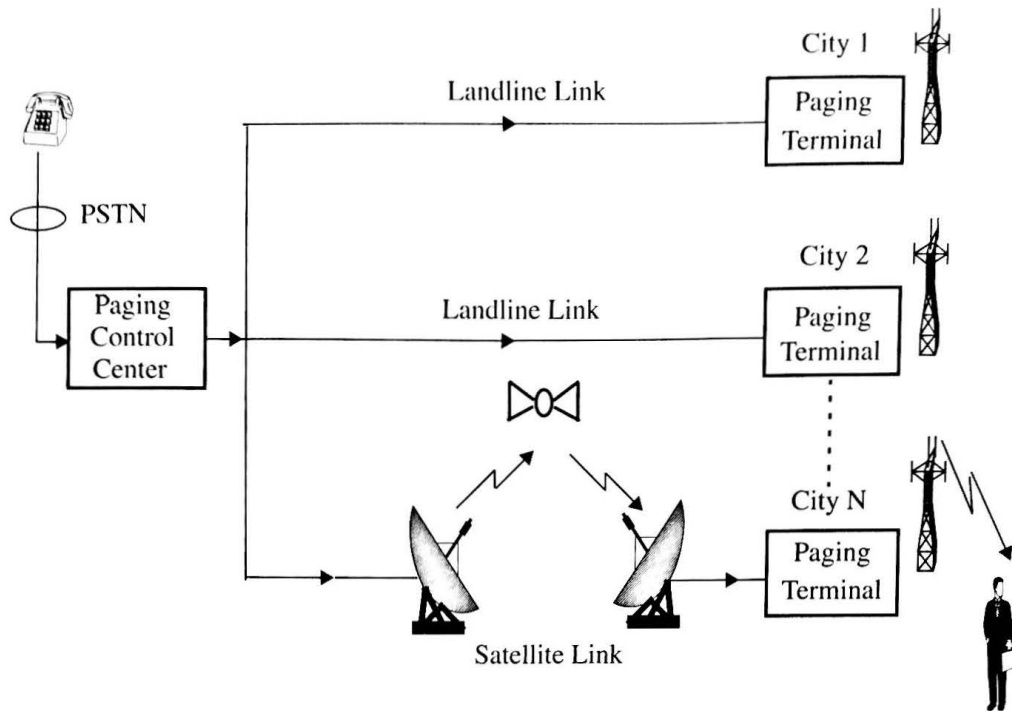


Figure 1.3 A wide area paging system. The paging control center dispatches pages received from the PSTN throughout several cities at the same time.

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.

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 bandwidths 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

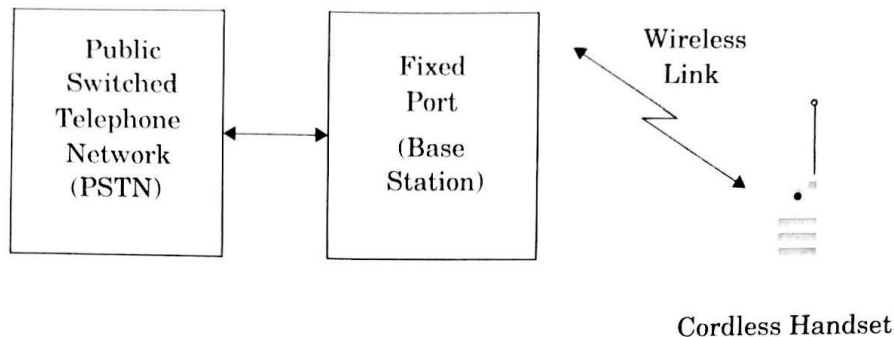


Figure 1.4 A cordless telephone system.

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.

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

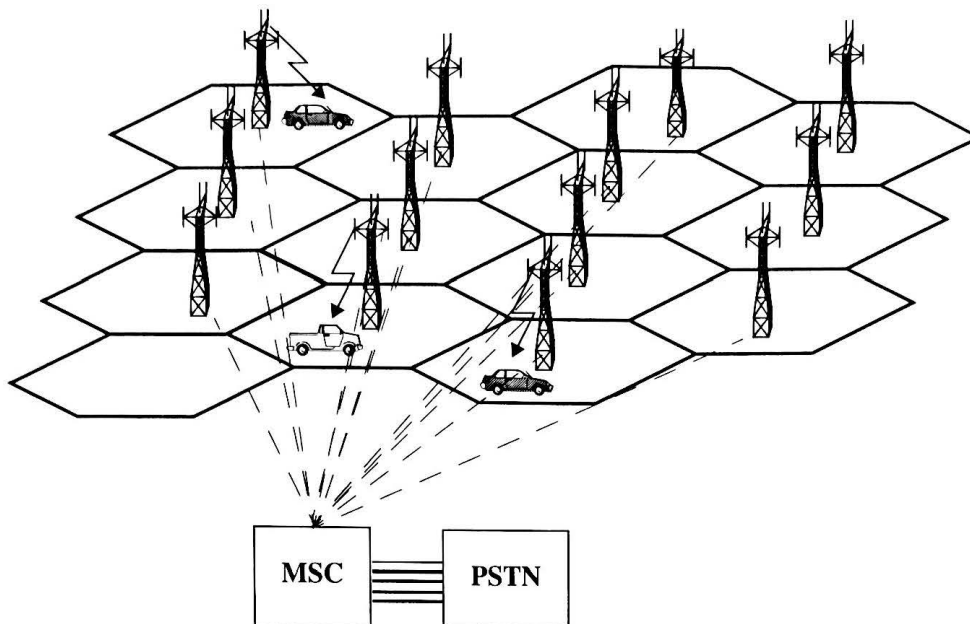


Figure 1.5 A cellular system. The towers represent base stations which provide radio access between mobile users and the mobile switching center (MSC).

serves as a bridge between all mobile users in the cell and connects the simultaneous mobile calls via telephone lines 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 11, supervisory and data messages 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 Tables 1.1 through 1.3, the control channels are defined and standardized over the entire geographic area covered and typically make up about 5% of the total number 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.

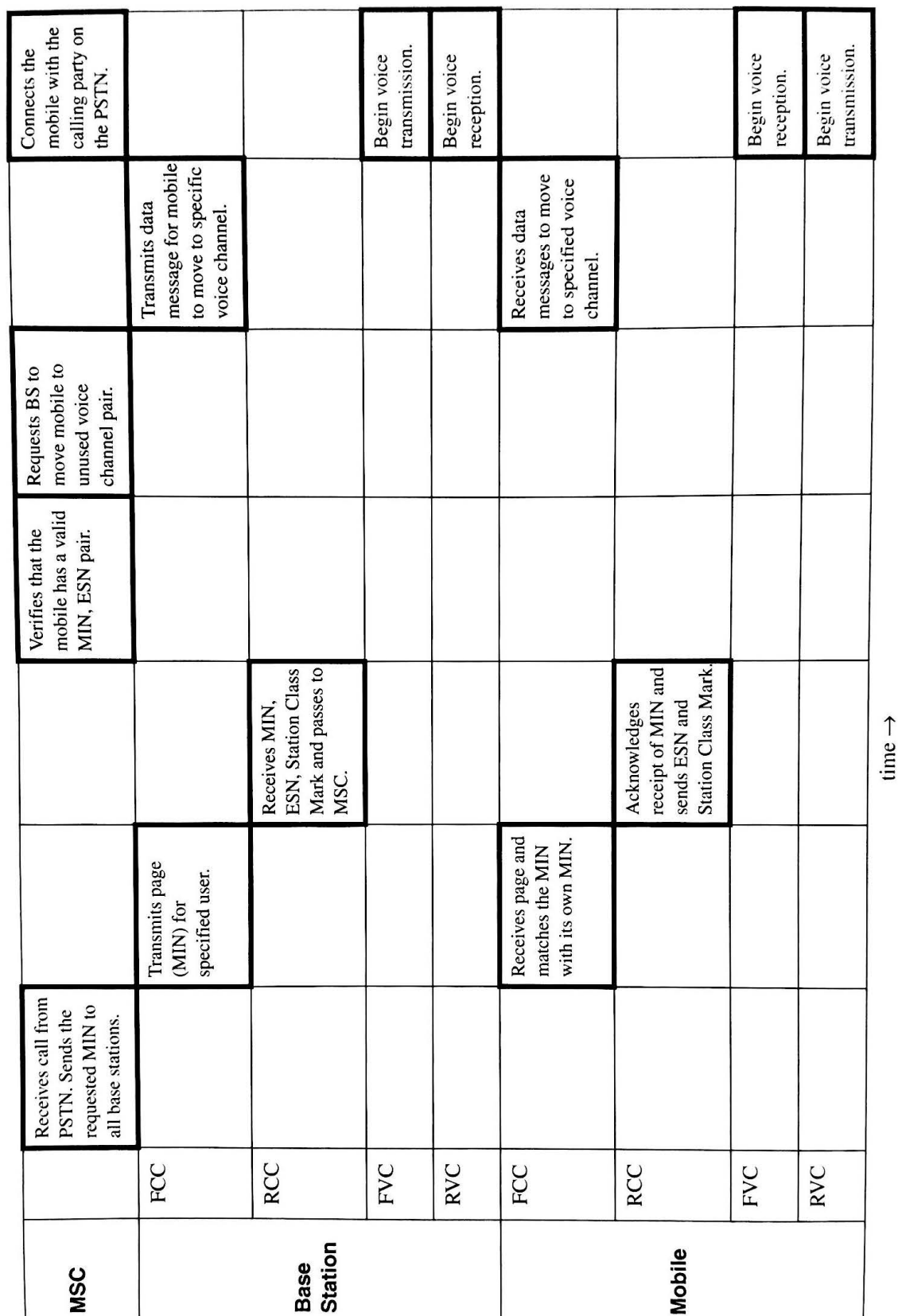


Figure 1.6 Timing diagram illustrating how a call to a mobile user initiated by a landline subscriber is established.

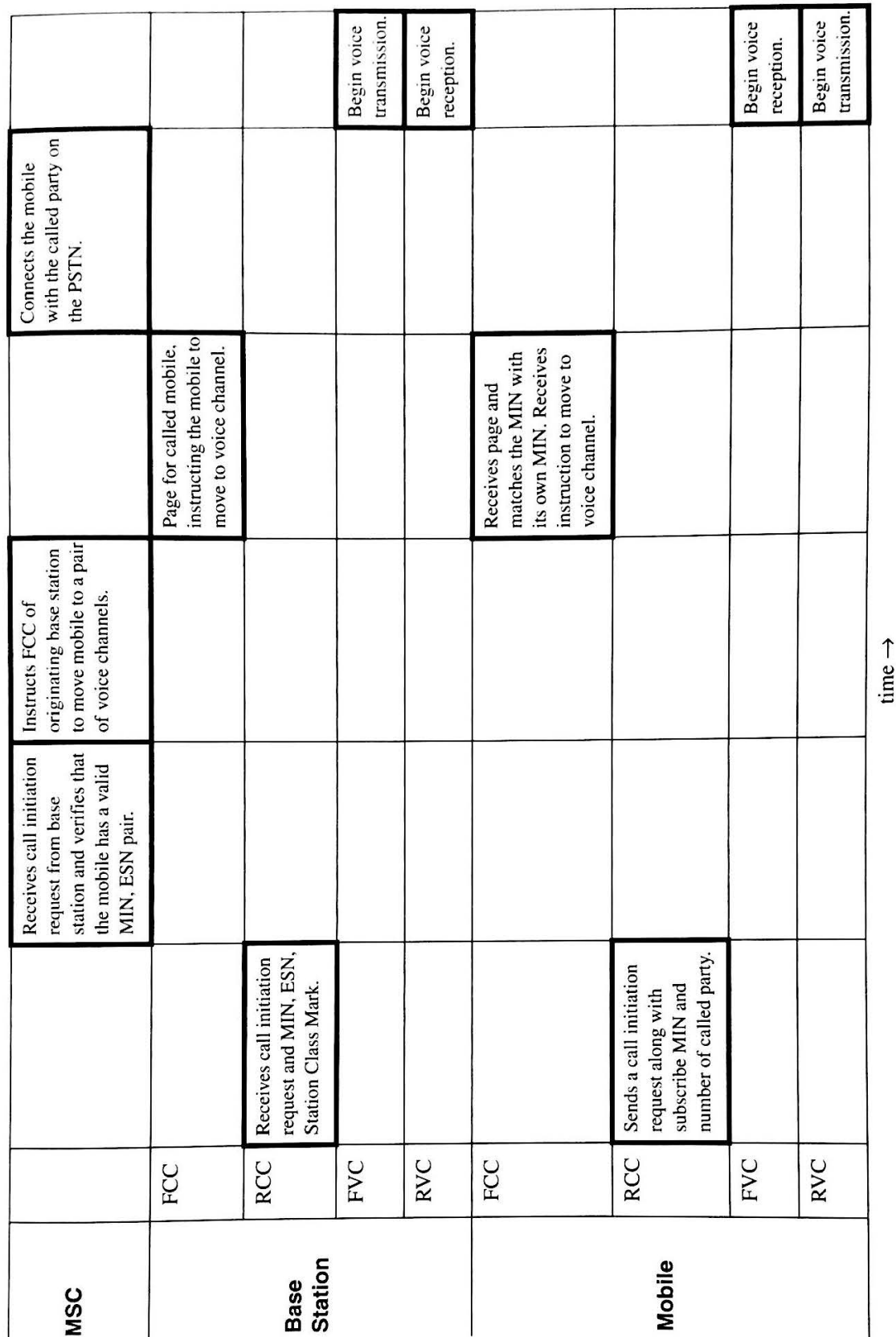


Figure 1.7 Timing diagram illustrating how a call initiated by a mobile is established.

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 accomplished over the FCC, since each roamer is camped on to an 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 10.

1.4.4 Comparison of Common Wireless Communication Systems

Tables 1.5 and 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 Tables 1.5 and 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

Table 1.5 Comparison of Mobile Communication Systems—Mobile Station

Service	Coverage Range	Required Infra-structure	Complexity	Hardware Cost	Carrier Frequency	Functionality
TV Remote Control	Low	Low	Low	Low	Infrared	Transmitter
Garage Door Opener	Low	Low	Low	Low	< 100 MHz	Transmitter
Paging System	High	High	Low	Low	< 1 GHz	Receiver
Cordless Phone	Low	Low	Moderate	Low	1–3 GHz	Transceiver
Cellular Phone	High	High	High	Moderate	< 2 GHz	Transceiver

Table 1.6 Comparison of Mobile Communication Systems—Base Station

Service	Coverage Range	Required Infra-structure	Complexity	Hardware Cost	Carrier Frequency	Functionality
TV Remote Control	Low	Low	Low	Low	Infrared	Receiver
Garage Door Opener	Low	Low	Low	Low	< 100 MHz	Receiver
Paging System	High	High	High	High	< 1 GHz	Transmitter
Cordless Phone	Low	Low	Low	Moderate	1–3 GHz	Transceiver
Cellular Phone	High	High	High	High	< 2 GHz	Transceiver

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.

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 range 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 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 3G 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 yet embody all of the concepts of an ideal PCN. Today, cellular and PCS are identical in functionality and differ only in frequency band.

Indoor wireless networking products are rapidly emerging and promise to become a major part of the telecommunications infrastructure within the next decade. As discussed in Chapter 2, 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 HIPERLAN standard for indoor wireless networks. Breakthrough products such as Motorola's 18 GHz Altair WIN (wireless information network) modem, that was not commercialized, and Avaya's (formerly NCR and Lucent)/ORiNOCO waveLAN computer modem have been available as wireless ethernet connections since 1990 [Tuc93] and are beginning to penetrate the business world. As we enter the 21st century, products are emerging that 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—has been 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 worldwide wireless networks should evolve and how worldwide 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 will 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 to 2025 MHz and 2110 to 2200 MHz was targeted by the ITU's 1992 World Administrative Radio Conference (WARC). In March 1999, ITU-R agreed to additional spectrum allocations that include the frequency bands 806 to 960 MHz, 1710 to 2200 MHz, and 2520 to 2670 MHz. This additional spectrum allocation was approved in May 2000 at the ITU World Radio Conference (WRC-2000). The types of modulation, speech coding, and multiple access schemes to be used in IMT-2000 were also locked down by the ITU Radio General Assembly in mid-2000. As discussed in Chapter 2, the selected radio interfaces for terrestrial wireless service include expansions of today's GSM and IS-95 CDMA, as well as a new time-code CDMA standard proposed by China.

Worldwide standards are also required for low earth orbit (LEO) satellite communication systems that were developed in the 1990s but which failed commercially at the turn of the century. 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 microcellular systems. However, satellite mobile systems were touted as offering tremendous promise for paging, data collection, and emergency communications, as well as for global roaming. In early 1990, the aerospace industry demonstrated the first successful launch of a small satellite on a rocket from a jet aircraft. This launch technique was pioneered by Orbital Sciences Corp. and was more than an order of magnitude less expensive than conventional ground-based launches and allowed rapid deployment, suggesting that a network of LEOs could be rapidly launched for wireless communications around the globe. While several companies, such as Motorola's Iridium, proposed systems and service concepts for worldwide paging, cellular telephone, and emergency navigation and notification in the early 1990s [IEE91], the capital markets have not supported mobile satellite systems in general.

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 undergoing a major telecommunications revolution that will provide ubiquitous communication access to citizens, wherever they are. The wireless telecommunications industry 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 Write an equation that relates the speed of light, c , to carrier frequency, f , and wavelength, λ .
- 1.2 If 0 dBm is equal to 1 mW (10^{-3} W) over a $50\ \Omega$ load; express 10 W in units of dBm.
- 1.3 Why do paging systems need to provide low data rates? How does a low data rate lead to better coverage?
- 1.4 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?
- 1.5 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.
- 1.6 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?
- 1.7 Between a pager, a cellular phone, and a cordless phone, which device will have the longest battery life between charging? Why?
- 1.8 Between a pager, a cellular phone, and a cordless phone, which device will have the shortest battery life between charging? Why?
- 1.9 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?
- 1.10 Modern wireless devices, such as 2-way pagers, and GSM phones, have sleep modes which greatly reduce the duty cycle of the power supply. Work Problem 1.9 above, then consider a wireless communicator that has three different battery states (1 mA in idle, 5 mA in wake-up receive mode, and 250 mA in transceiver mode). Consider the effects of different duty cycles and transmit times to see the wide range of battery lifetimes one may expect before recharging. Plot your results of battery lifetime as a function of the duty cycles and durations of the wake-up mode. Hint: 1 Amp-hour describes a battery that can supply 1 Amp of current for a period of one hour. This same battery may supply 100 mA for 10 hours, and so on.
- 1.11 Assume a CT2 subscriber unit has the same size battery as the phone in Problem 1.9, 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 1.9. Recompute the maximum talk time for the CT2 handset.
- 1.12 Why would one expect the CT2 handset in Problem 1.11 to have a smaller battery drain during transmission than a cellular telephone?
- 1.13 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.
- 1.14 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.

- 1.15 Assume that a GSM, an IS-95, and a US Digital Cellular (IS-136) 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. Review Appendix B to determine how noise figure might impact your answers, and describe the importance of receiver noise figure in actual systems.
- 1.16 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?
- 1.17 There have been a large number of wireless standards proposed throughout the world in the past 18 months. Using the trade literature and the Internet, find three new wireless standards (one each for the paging, PCS, and satellite market sectors), and identify the multiple access technique, continent of operation, frequency band, modulation, and channel bandwidth for each standard. The standards that you identify must be new (i.e., do not appear in Tables 1.1, 1.2, or 1.3). Include a paragraph description of each standard, cite the references you used to learn about it, and describe why the standard was proposed (what niche or competitive advantage does it offer). Challenge: Try to find standards that are not yet popular on your continent.
- 1.18 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.
- 1.19 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?
- 1.20 Based on the proliferation of wireless standards throughout the world, discuss how likely it is for the IMT-2000 vision to eventually be adopted. Provide a detailed explanation, along with probable scenarios of services, spectrum allocations, and cost.
- 1.21 This assignment demonstrates how rapidly wireless has emerged in the telecommunications field. You will be investigating new services, systems, and technologies for wireless communications that have been proposed in the past couple of years. Using the library, the WWW, industry and consumer web pages, and various trade magazines and journals, learn and describe the present state of technology for these new systems.

To proceed, consider the following categories of wireless communications systems: a) Wireless Local Loop (also called Fixed Wireless Access); b) Broadband Wireless Communications (also known as Local Multipoint Distribution Service—LMDS in the US, LMCS in Canada and Europe); c) Third Generation Wireless Systems (also called “3G”); d) Wireless Local Area Networks (WLANs); e) Satellite/Cellular wireless systems; and f) in-home wireless networks and small office/home office (SOHO) appliance data networks. For each of these six broadband wireless system areas, do the following:

- (a) Carefully define each of the six broad categories of wireless systems listed above. Your definitions should provide compelling reasons why such systems have been proposed, what type of user the system is intended to serve, and what are the technical enablers and justifications given for the new systems. That is, why are the new systems emerging, and what are the compelling reasons for them? What are the target markets, applications, and eventual adoption rates being planned for?
- (b) To help with (a), it is useful to determine the international or national standards bodies involved with the creation and definition of such systems. Using the library, journals, and the WWW, determine the major standards bodies involved with each of the six systems, on both a national and international level. Identify the key organizations and key players who are helping to create a forum or who are providing technical leadership for each of the six systems, on each of the major continents. Describe these organizations and provide references (i.e., web address or citations in the literature) so that others can learn more about these organizations and how they work to forge the standards.
- (c) Using the references found in (a) and (b), you can now begin to determine the technical issues and specifications for the emerging wireless systems. Provide detailed technical written descriptions of the various technologies which have been proposed to satisfy the broad system concepts, and provide a list of key technological attributes of each proposal. Note: In many cases, there will be multiple system proposals for each broad system concept. Describe the technical attributes of each of the competing technologies and list, in tabular form similar to Tables 1.1–1.3, how the different parts of the world are approaching these broad system concepts, and what carrier frequencies, data rates, modulation techniques, multiple access techniques, RF bandwidths, and baseband bandwidths are being proposed. Also illustrate unique or interesting technical issues surrounding the various proposals for each system concept.