

# Introduction to Wireless Communication Systems

**T**he 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, as the fifth generation (5G) of wireless takes hold.

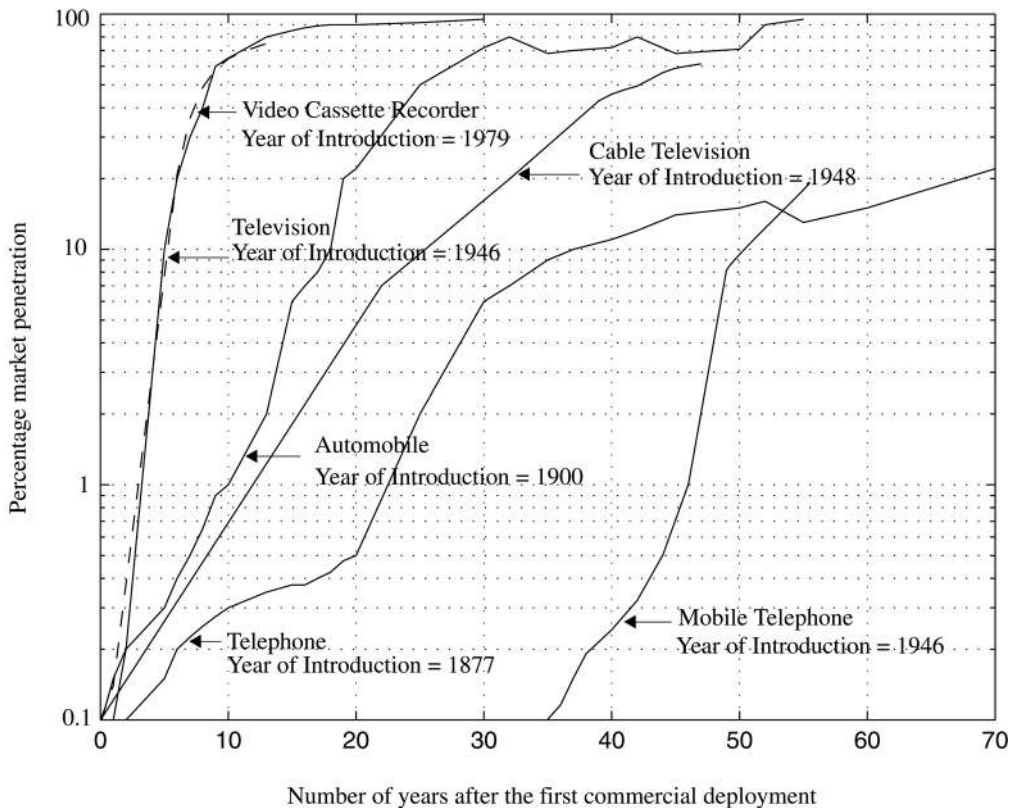
## 1.1 Evolution of Mobile Radio Communications

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



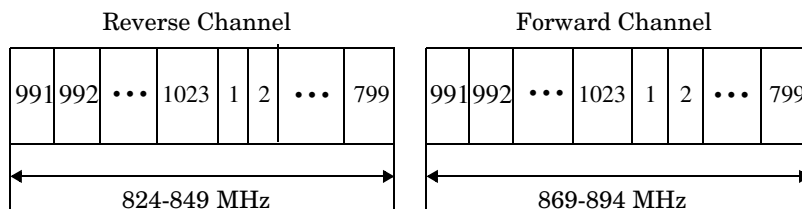
**Figure 1.1** The growth of mobile telephony as compared with other popular inventions of the 20th century.

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 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
<b>AMPS</b>	Cellular	1983	FDMA	824-894 MHz	FM	30 kHz
<b>NAMPS</b>	Cellular	1992	FDMA	824-894 MHz	FM	10 kHz
<b>USDC</b>	Cellular	1991	TDMA	824-894 MHz	$\pi/4$ -DQPSK	30 kHz
<b>CDPD</b>	Cellular	1993	FH/ Packet	824-894 MHz	GMSK	30 kHz
<b>IS-95</b>	Cellular/ PCS	1993	CDMA	824-894 MHz 1.8-2.0 GHz	QPSK/ BPSK	1.25 MHz
<b>GSC</b>	Paging	1970s	Simplex	Several	FSK	12.5 kHz
<b>POCSAG</b>	Paging	1970s	Simplex	Several	FSK	12.5 kHz
<b>FLEX</b>	Paging	1993	Simplex	Several	4-FSK	15 kHz
<b>DCS-1900 (GSM)</b>	PCS	1994	TDMA	1.85-1.99 GHz	GMSK	200 kHz
<b>PACS</b>	Cordless/ PCS	1994	TDMA/ FDMA	1.85-1.99 GHz	$\pi/4$ - DQPSK	300 kHz
<b>MIRS</b>	SMR/PCS	1994	TDMA	Several	16-QAM	25 kHz
<b>iDen</b>	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
<b>ETACS</b>	Cellular	1985	FDMA	900 MHz	FM	25 kHz
<b>NMT-450</b>	Cellular	1981	FDMA	450-470 MHz	FM	25 kHz
<b>NMT-900</b>	Cellular	1986	FDMA	890-960 MHz	FM	12.5 kHz
<b>GSM</b>	Cellular /PCS	1990	TDMA	890-960 MHz	GMSK	200 kHz
<b>C-450</b>	Cellular	1985	FDMA	450-465 MHz	FM	20 kHz/ 10 kHz
<b>ERMES</b>	Paging	1993	FDMA	Several	4-FSK	25 kHz
<b>CT2</b>	Cordless	1989	FDMA	864-868 MHz	GFSK	100 kHz
<b>DECT</b>	Cordless	1993	TDMA	1880-1900 MHz	GFSK	1.728 MHz
<b>DCS-1800</b>	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
<b>JTACS</b>	Cellular	1988	FDMA	860-925 MHz	FM	25 kHz
<b>PDC</b>	Cellular	1993	TDMA	810-1501 MHz	$\pi/4$ - DQPSK	25 kHz
<b>NTT</b>	Cellular	1979	FDMA	400/800 MHz	FM	25 kHz
<b>NTACS</b>	Cellular	1993	FDMA	843-925 MHz	FM	12.5 kHz
<b>NTT</b>	Paging	1979	FDMA	280 MHz	FSK	12.5 kHz
<b>NEC</b>	Paging	1979	FDMA	Several	FSK	10 kHz
<b>PHS</b>	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