1 Introduction to wireless communications and digital broadcasting

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The purpose of communication engineering is to transmit information from its source to the destination over some distance away. A basic communication system mainly consists of three essential components: transmitter, channel (wired or wireless), and receiver. Figure 1.1 shows a typical point-to-point one-way communication system. For a two-way system, a receiver and a transmitter are both required on each side.

The transmitter transforms the input signal to a transmission signal that is suitable for the characteristic of the channel. Since a channel is always varying with time, and the input signal to the system differs, the transmitter processes the input signal to produce a suitable signal for transmission. This generally includes the modulation and the coding. After being processed by the transmitter, the transmitted signal goes into the channel. The channel can be any medium or interface suitable for the transmission and it connects the transmitter and the receiver. The channel may be the laser beam, coaxial cable, or radio wave. During the transmission, there are various unwanted effects on the signals. Attenuation and power loss reduce the signal strength and make the detection difficult at the receiver. Besides the power loss and the attenuation, the channel may always introduce some undesired signals. These signals may be random and unpredictable signals that exist in nature, such as solar radiation, or the signals produced by other transmitters or machines. We call the former type of undesired signal “noise” and the latter type “interference.” If the interfering signals occupy different frequencies of the desired signal, using proper filters can remove these interferences. In comparison, the random noise that superimposes on the information-bearing signals is hard to completely eliminate by the filter and the remaining noise will inevitably corrupt the desired signal. The power ratio of received signal over noise decides the channel capacity which is one of the basic system performance parameters. After the receiver picks up the signal from the channel, it will do some filtering to compensate for the power loss, followed by demodulation and decoding to recover the original input signals.

Wireless transmission of information has experienced fast growth in the past few decades. A basic wireless system generally contains radio frequency (RF) front-end and baseband processing. From the application point of view, wireless systems can be categorized into two types: *unicasting* and *broadcasting* [1]. Unicasting is used for symmetric

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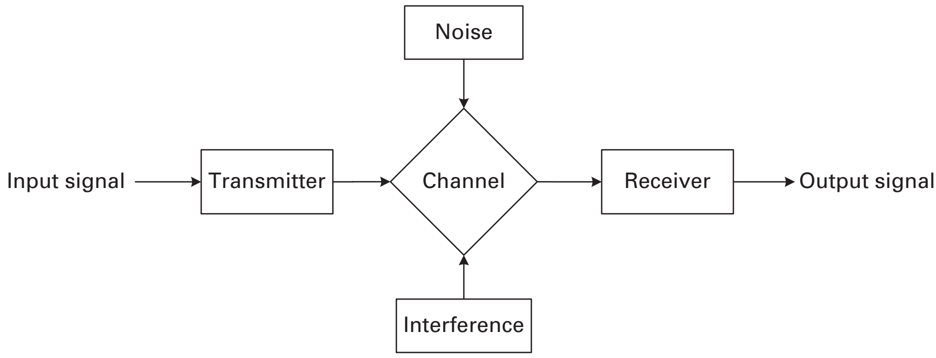

Figure 1.1 Elements of a communication system.

applications such as voice telephony and wireless data access in a bi-directional channel. Broadcasting is used for distribution of audio/video and other multimedia content over a reliable and unidirectional channel. As a major unicast application, the cellular network emerged from the first generation analog voice system, followed by its second-generation digital system providing basic data services. Now we are at the stage between the third generation and pre-fourth generation system. It offers both high-speed Internet data access and high-quality voice services. Owing to the different application characteristics, broadcasting evolves along a different trajectory which will also be discussed later in this chapter. Along with other networks, the ubiquitous wireless applications make multi-radio coexistence inevitable and the hybrid network converging both unicasting and broadcasting is becoming a notable trend [1].

Organized into four sections, this chapter provides a brief overview of the general principles of wireless broadband communications and broadcasting. We first review the wireless evolution by looking at two major applications: cellular network and TV broadcast network. Then, the discussion focuses on some key techniques including multiple-input multiple-output technique (MIMO), orthogonal frequency division multiplexing (OFDM), and cognitive radio. In the final section, we will present a summary and further discussions.

1.1 Evolution of mobile cellular networks

The cellular telephone system is one the most successful applications of wireless communication. A cellular network consists of multiple cells. Each cell contains one base-station (BS) and several mobile stations. The base-station of each cell is connected and controlled by the mobile switching center (MSC) through a dedicated backhaul link. The MSC keeps track of users' information. The MSCs are connected by the gateway MSC (GMSC) to connect the cellular users with customers using other wireless providers. The GMSC is the termination of the public switched telephone network to provide wide range communication. The general system model for cellular systems is shown in Figure 1.2.

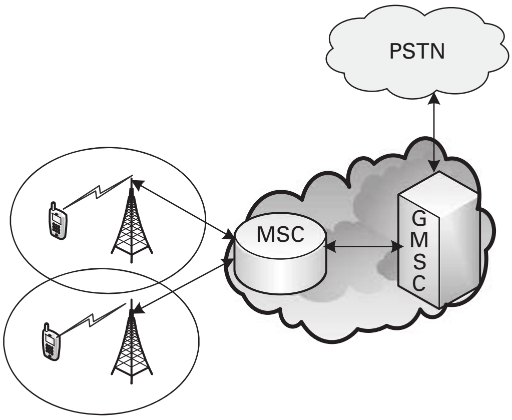

Figure 1.2 The general cellular system model.

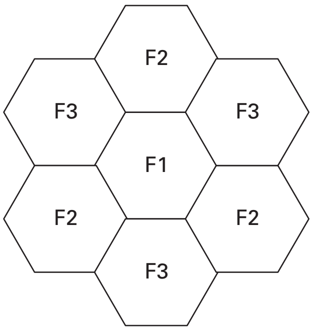

Figure 1.3 An example of frequency reuse in cellular networks.

In 1915, wireless voice transmission was established between New York and San Francisco, a distance of 2500 miles, which is a milestone in wireless communication. Wireless communication was a priority for the military until 1946 when AT&T was allowed to provide the world's first mobile telephone service. In 1946, 25 cities in the United States had built up a public mobile telephone service. These initial systems used one high-power BS to cover an entire metropolitan area without the frequency reuse which is called macrocell technology. Besides the deficiency of radio technologies, the system capacity was severely limited at that time [2]. To solve this problem, the cellular concept was proposed by AT&T Bell Lab researchers in the 1960s [3]. Cellular systems have the property that the power of a signal decreases with distance. Hence, the interference between two users that are spatially far from each other can be neglected. This means that two users far from each other can use the same frequency, which can greatly enhance the system capacity. An example of the frequency reuse is shown in Figure 1.3, wherein F1, F2, and F3 represent different frequency bands. Each hexagon represents a cell, in which users share a certain frequency band as depicted in the figure.

1.1.1 First-generation cellular systems

The two landmark technologies of the first-generation cellular systems (1G) are the application of the cellular concept, and the relative handoff technology. The handoff technology is used when users travel between cells during a conversation in order to maintain the service. The first generation of cellular systems was designed in the late 1960s. However, it was not launched until the early 1980s because of regulatory delays. First-generation networks use Frequency Division Multiplexing Access (FDMA) to transmit analog voice signal through wireless channels. In 1979, NTT DoCoMo established the first commercially automated cellular network. Nordic Mobile Telephone (NMT) was the first to support international roaming. In 1982, the Advanced Mobile Phone System (AMPS) went operational, which was the first commercial analog system in the United States [4]. However, the 1G system only provides voice service over circuit switching.

1.1.2 Second-generation cellular systems

The second-generation (2G) mobile phone systems emerged in the early 1990s. It is based on digital communication, which is the key difference between 2G and 1G communication. The digitalization is realized by adding a digital-to-analog (D/A) converter before the RF transmitter, and an analog-to-digital (A/D) converter after the RF receiver. Compared to analog systems, digital systems have the following advantages:

(1) Better security. Digital signals can be easily encrypted, and all digital cellular systems have their encryption part. In contrast, analog systems have no security which means an eavesdropper can easily intercept a user's identification number.
(2) Higher communication quality. In digital systems, error detection and correction by encoding and decoding can be applied to achieve a higher communication quality. However, analog data form is susceptible to interference which results in a highly variable reception quality.
(3) Higher frequency efficiency. Digital data can be compressed, so digital systems have higher spectrum efficiency.

Furthermore, 2G digital systems also have longer battery life, higher capacity, higher data rate, and cheaper digital equipment than analog systems. The cellular phones' great market potential has led to a proliferation of 2G standards. While 2G cellular systems initially supported only voice services, later on these systems also supported data services such as short messaging and Internet access. In the same way as 1G systems, 2G systems also use circuit-switching for data transmission. There are four main standards for 2G systems: Global System for Mobile (GSM) communications; Digital AMPS (D-AMPS); Code Division Multiple Access (CDMA) IS-95; and Personal Digital Cellular (PDC). However, these standards are all incompatible.

1.1.3 Third-generation cellular systems

With the development of the 2G technique and the wide application of the cellular phone, the demands for data services were growing. This trend stimulated the emergence of the third-generation (3G) technology. While 2G systems were designed to carry speech and low bit-rate data, 3G systems target at higher data rate services. The use of packet-switching for data transmission distinguishes the 3G technology from 2G technology. The 3G standards were defined as International Mobile Telecommunications-2000 (IMT-2000) by the International Telecommunications Union (ITU). The IMT-2000 standard aims to support high-speed voice and data services, and to support seamless global roaming and seamless delivery of services. According to the IMT-2000 specification, a 3G system must simultaneously support speech and data services, and provide at least 200 Kbps peak data rates. The three dominant 3G standards are Wideband CDMA (WCDMA), CDMA2000, and Time Division-Synchronous CDMA (TD-SCDMA). The first 3G network was deployed in Japan in 2001. The 3G networks can provide data rate ranging from 384 kbps to 2 Mbps; while 2G networks support data rate ranging from 9.6 kbps to 28.8 kbps. Broadband should be with instantaneous bandwidths greater than 1 MHz and support data rates greater than 1.5 Mbps [5]. Intel defines it as a continuum of co-existing, overlapping technologies that enable high-speed communications [6]. Hence, 3G belongs to broadband communications [7].

During the development of 3G systems, CDMA2000 1X and GPRS (also called 2.5G) were developed as extensions of 2G networks. 2.5G techniques have some features of 3G systems. For example, CDMA2000 1X can theoretically support 307 kbps as the maximum data speed. Beyond CDMA2000 1X, EDGE system theoretically meets the requirements of 3G systems [8]. In the mid 2000s, High-Speed Downlink Packet Access (HSDPA), as an evolution of 3G technology, began to be implemented. High-Speed Downlink Packet Access allows Universal Mobile Telecommunications System (UMTS) based networks to have a higher data rate and capacity. The downlink speed of current HSDPA can be 1.8, 3.6, 7.2, and 14.0 Mbps, while HSPA+ will provide a higher downlink speed of up to 84 Mbps, according to Release 9 of the 3rd Generation Partnership Project (3GPP) standards [9].

1.1.4 Future broadband wireless communications

In the future, different wireless communication standards are expected to be integrated into one unique communication system, and such a system is called the fourth generation (4G). Fourth generation will enable a comprehensive and secure all-IP based solution, such as IP phone, ultra-broadband Internet access, HDTV broadcast, and stream multimedia. The 4G system will provide full mobility and connectivity, which requires free roaming from standard to standard or from service to service. In July 2003, International Telecommunication Union (ITU) made a requirement for 4G system known as IMT-Advanced standard: First, the transmission data rate should be above 1 Gbps at the stationary condition. Second, the transmission

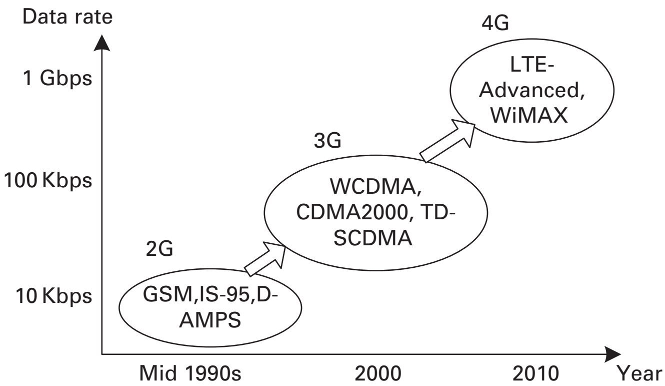

Figure 1.4 The evolution of communication systems.

data rate should be above 100 Mbps at moving speed [10]. Both 3GPP Long Term Evolution (LTE) and Worldwide Interoperability for Microwave Access (WiMAX) are candidates for 4G systems. The evolution of communication systems is shown in Figure 1.4.

To meet the high-level performance requirement, the first 3GPP LTE relies on advanced physical layer technologies, such as MIMO techniques, OFDM techniques, and cognitive radio [11]. Long Term Evolution cannot fully meet the IMT Advanced requirements. Hence, LTE-Advanced was proposed as a candidate for IMT Advanced standard. LTE advanced was formally submitted to ITU-T in fall 2009 by the 3GPP organization and is expected to be released in 2012. Parallel with LTE, IEEE 802.16m will be one of the 4G version and will be backward-compatible with the existing IEEE 802.16e. Many 4G air interfaces are now being examined. The 4G systems have to be cost-effective and quality of service (QoS) driven. Potential 4G technologies include:

(1) Efficient modulation techniques, such as the OFDM technology which can easily combat the multipath effect in broadband systems;
(2) Advanced antenna technologies, such as MIMO techniques that can combat interference and greatly enhance the system capacity;
(3) Intelligent systems, such as cognitive radio that can adjust with the varying transmission conditions;
(4) Advanced encoding and decoding techniques, such as turbo coding and low-density parity-check codes (LDPC);
(5) Wireless access technologies, such as Orthogonal Frequency-Division Multiple Access (OFDMA) and Multiple Carrier Code-Division Multiple Access (MC-CDMA);
(6) Multiple systems' cooperation and convergence, such as broadcast and cellular network hybrid.

1.2 Evolution of broadcast network

In this section, a brief overview of current existing broadcast systems is given. As the major broadcast application, TV networks provide video and audio services to a large number of users. Therefore, most of the discussions are based on existing TV technologies.

1.2.1 Analog broadcast system

The earliest wireless broadcast technology can be traced back to the year 1900 when Guglielmo Marconi sent his famous Morse code from England to Canada. At the early stage, broadcasting was mainly used for radio and wireless telegraph until the emergence of TV, which utilized the high-frequency radio wave to transmit TV signals.

In the early stages, all the information was encoded and transmitted as analog signals. Analog transmission is the traditional method for wireless broadcasting. It uses a continuous carrier signal whose amplitude, frequency, or phase varies in proportion to the analog message (voice, image). Frequency modulation (FM) and amplitude modulation (AM) are widely used in analog communications [12]. Different analog TV broadcast systems have different frequencies, frame rates, and resolutions. In 1950s, the International Telecommunication Union (ITU) standardized the monochrome combination for black-and-white TV by using the capital letters A to N. Later on, information of the hue and saturation in the picture were added as the signal parameters for color television. Nowadays, there are three standards for the coding and transmission of color TV signals, ANTSC (American National Television Systems Committee), PAL (Phase Alternation Line) and SECAM (Séquentiel Couleur Avec Mémoire). The ANTSC is mainly used in North America while the other two are applied in European and Asian countries.

Compared to digital systems that require complicated multiplexing and timing synchronization, analog transmission is a low-cost alternative for broadcasting. Nowadays, analog broadcasting is still very popular, especially for short-distance broadcasting. However, in long-distance and high-throughput transmissions, analog broadcasting has poor performance due to severe signal attenuation. Recently, many countries have completely ceased analog transmissions on certain media, such as television, for technological and economical reasons.

1.2.2 Digital broadcast system

In the 1990s, with the development of digital technology, digital communication attracted more and more attention. Comparing to analog signals, the transmission of information by digital signals can ensure better quality and has higher transmission rates. Also, digital signals can better resist the interference than analog signals. Some problems caused by channel noise in analog television have been solved, such as ghosting images, unstable images, and reduction of the image quality. In digital television systems, the audio and video are synchronized before the transmission, so the received signals are almost complete. Otherwise, the received TV signals cannot be decoded and displayed. With the completeness of the signals, the digital TV program can still be watched when it experiences interference. Recently, the digital signal has gradually replaced the traditional analog signal in TV broadcasting. In some developed countries, including the United States and Germany, this replacement has been made. In the United States, since June 11, 2009, all on-the air TV signals have adopted the Advanced Television Systems Committee Standards (ATSC), and high-power analog signal transmissions have been ceased by Federal Communications Commission (FCC) [13].

Digital broadcasting uses digital data rather than analog waveform to carry broadcast information over television channels or assigned radio frequency bands. Unlike analog communication, digital broadcasting only transmits discrete messages. In the baseband transmission, information is represented by a sequence of pulses while a finite set of predetermined waveforms are used for presentation in passband transmission. The modulation as well as the corresponding demodulation and detection are carried out by modem. The data transmitted are in the form of digital symbols. An analog signal such as a voice signal is first sampled into a stream of bits using PCM (pulse-code modulation) or some other source-coding technique. Generally, the source coding and decoding are completed by encoder and decoder at the transmitting and receiving ends, respectively [14].

Besides its robustness to noise and interference, digital TV also has several other advantages over analog TV. One of the most significant advantages is its high spectrum efficiency. The bandwidth needed for digital TV broadcasting can be flexibly determined by the compression level and the transmitted image resolution. In this way, the service providers can broadcast more digital information or offer the high-definition television service (HDTV) within the same spectrum bandwidth. Furthermore, digital TV also supports some non-television services such as multimedia, multiplexing (playing more than one program simultaneously), and translating into other languages.

Today, most countries have adopted digital television as the main direction of future TV services. There are four different families of digital TV standards used in different regions, as is shown in Figure 1.5 [15].

ATSC Terrestrial

In the early 1990s, the Advanced Television Systems Committee developed a set of standards known as ATSC used for digital television transmission over terrestrial networks. Now, it is the standard of digital TV service in North America. ATSC specifies the design of a system transmitting the digital video, audio, and data over 6-MHz channels and the information rate is 19.29 Mbps. The same bandwidth is used in the design of the ATSC as traditional analog NTSC TV channels. After MPEG-2 compression and multiplexing, the signals are output as streams that can be modulated in various ways based on the different transmission methods.

(1) TV broadcasters use 8-level vestigial sideband modulation (8VSB) to deliver the video and audio information at a maximum rate of 19.39Mbps.

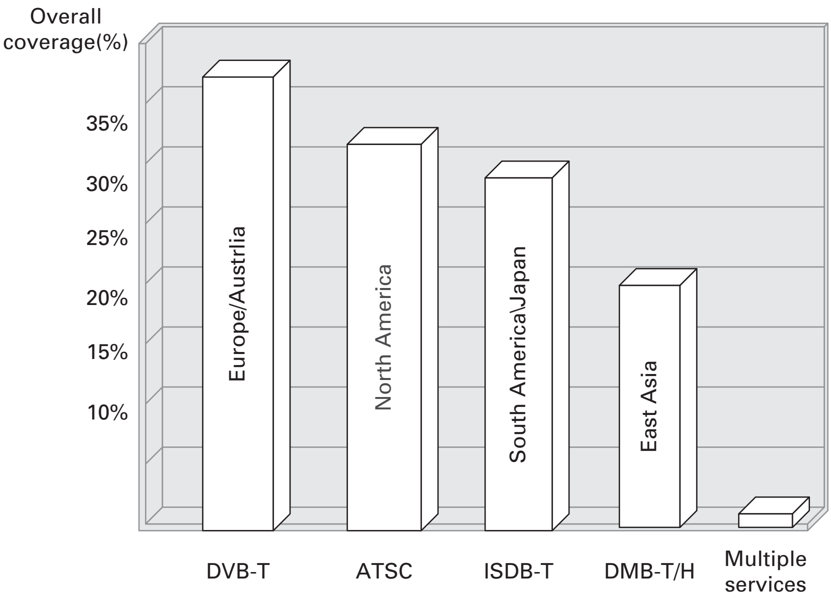

Figure 1.5 Different standards of DTT broadcasting systems.

(2) Cable TV stations operating in higher signal-to-noise ratio (SNR) environment can use the 16VSB defined by ATSC or the QAM to achieve a rate of 38.78 Mbps.

For HDTV, the ATSC defined a series of standards for wide screen 16:9 images and up to 1920 × 1080 pixels, which is over six times the resolution in the previous standards. Besides, it also supports many other image sizes. The type of formats can be broadly divided into two categories: High-definition television (HDTV) and standard definition TV (SDTV).

High-definition TV, transmitted through digital TV, can support several different formats. For example, 1280 × 720 pixels (known as *720p*) and 1920 × 1080 pixels (known as *1080p*). Each of these formats uses 16:9 ratio. However, traditional analog channels cannot transmit HDTV signals.

In contrast, SDTV can only use one format which depends on the technology used for transmission in different countries. In NTSC countries, the 640 × 480 format is used for 4:3 broadcasts and the 704 × 480 format is applied in 16:9 broadcasts. Meanwhile in PAL countries, the 720 × 576 is used in PAL for both. However, in order to save the bandwidth, broadcasting service providers may reduce resolutions [16].

DVB-T

In the 1990s, a set of standards for digital broadcasting of television, sound, and data services were adopted by the European Telecommunications Standards Institute. They have been used for cable TV, broadcast signal transmission, and satellite communication. Among all the standards, ETS 300 744 is assigned to Digital Video Broadcast-Terrestrial (DVB-T). The DVB-T standard specifies a system transmitting high-quality digital

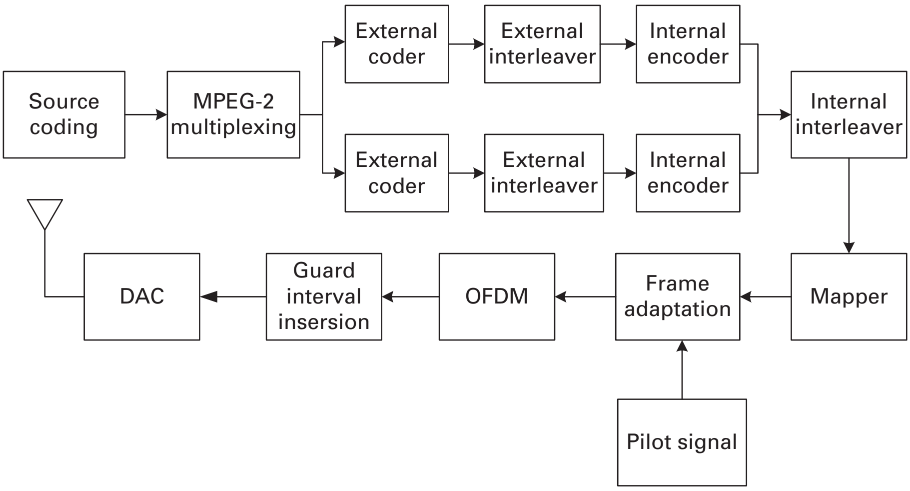

Figure 1.6 Scheme of a DVB-T transmission system.

video, audio, and data over the existing 7MHz or 8MHz channels. The digital information rate ranges from the minimum of 4.98 Mbps to the maximum of 31.67 Mbps.

In DVB-T, the data is transmitted as a series of blocks at some symbol rate during the transmission. This technique is called Coded Orthogonal Frequency-Division Multiplex (COFDM) transmission and a guard interval is used. The build-in of the guard intervals and equalization in the COFDM system greatly enhance the reception efficiency and the receiver is able to deal with the severe multipath attenuation. In some specific areas, DVB-T supports the single-frequency network (SFN) operation which allows several base-stations to simultaneously transmit the identical information on channels at the same frequency. In this case, the signals from different base-stations need to be accurately synchronized. The synchronization is based on the information attached in the bit stream and completed when the transmitter is referenced to GPS. Figure 1.6 gives the major components of a DVB-T system.

Although DVB-T is quite similar to the ATSC on the channel coding and transmission techniques, it uses a completely different modulation method. Due to the unique requirements of the base-stations and networks in Europe, SFN is used in most European countries since it can utilize the available channels more effectively. The COFDM system is selected as the most suitable. In SFN, a program is broadcasted by all base-stations on the same channel. The signals from different stations are precisely synchronized to the same reference signal. At the receiving end, a receiver may receive signals from more than one base-station with different delays, and the strength of the signal varies with time [17].

ISDB-T

Integrated Services Digital Broadcasting (ISDB) is the standard developed for Japanese digital TV and radio stations. It consists of ISDB-S, ISDB-T, ISDB-C for usages in satellite, terrestrial, and cable TV. All these three schemes are based on MPEG-2 coding