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INTRODUCTION TO INFORMATION NETWORKS

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1.1 INTRODUCTION

In the eyes of an engineer, the complexity of an industry relates to the challenges in implementation, size of the market for the industry, and the impact of the technology in this industry on human life. Everyday we use information networks and information technology more than any other technology – for social networking in both professional and personal aspects of our lives. The heart and the enabler of this technology is the *information networking industry*, which brings us mobile and fixed telephone services and connects us to the Internet in the home, office, and on the road, wherever we are. Although the infrastructure of the information networking industry is not seen by the public because it is mostly buried under the ground or it is propagating in the air invisibly, it is the most complex technology to implement, it owns the largest market size by far among all

Networking Fundamentals: Wide, Local and Personal Area Communications, by Kaveh Pahlavan and Prashant Krishnamurthy

industries, and it has enabled us to change our lifestyle to the extent that we often refer to our era as “the age of information technology.”

To have an intuitive understanding of the size of the information networking industry it is good to know that the size of the budget of AT&T in the early 1980s, before its divestiture, was close to the budget of the fifth largest economy of the world. AT&T was the largest public switched telephone network (PSTN) company in the world and its core revenue at that time was generated from the plain old telephone service (POTS) that was first introduced in 1867. During the past two decades, the cellular telephone industry has augmented the income of the prosperous voice-oriented POTS with subscriber fees from more than 3 billion cellular telephone users worldwide. Today, the income of the wireless industry dominates the income of the wired telephone industry. While this income is still by far dominated by the revenue of the cellular phones, smart mobile terminals are gradually changing this characteristic by bringing more Internet-oriented applications into the terminal. In the mid 1990s, the Internet brought the computer and data communications and networking industry from a relatively smaller business-oriented office industry to an “everyday and everybody” use home-oriented industry that soon generated an income comparable to that of a voice-oriented POTS and the wireless industry. At the time of writing, the revenue of the information networking *industry* is dominated by the combined income of the wired and wireless telephone services over the PSTN and the Internet access industries, with total annual revenue of a few trillion dollars, which makes it one of the largest industries in the world.

At the start of the year 2008, the number of mobile phone subscriptions in the world had already passed 3 billion, with a worldwide average penetration rate of close to 50%, making the mobile phone the most widespread and adopted technology in the world. At the same time, close to a billion people around the world have access to the Internet or equivalent mobile Internet services using a mobile phone, a laptop, or a personal computer. In June 2007, Apple lunched the iPhone, which opened a new dimension in the integration of computer, communication, and navigation devices in a mobile handheld terminal. Around 4 million devices were sold during the first 200 days [MOB08], and in the first quarter of business it turned in to the third best-selling smartphone in the world [ARS08]. The third-generation (3G) iPhone introduced in July 2008 sold 1 million in the first 3 days [WAC08]. The iPhone provides built-in mobile user-friendly applications for video streaming, audio storage, and localization, as well as a number of popular applications, such as e-mail access, stock market reports, weather condition reports, calendar, and notebooks, on top of the traditional mobile phone and short messaging. This range of applications uses location-aware and secure broadband wireless access technologies provided through cellular networks, WiFi wireless local area networks (WLANs), and Bluetooth-based wireless personal-area networks (WPANs) to connect to the Internet and the PSTN backbones.

The authors believe that the information network technologies which enable smartphones to integrate traditional communication and Internet applications provide a suitable framework for teaching a basic course to introduce the fundamentals of modern information networks to students. The objective of this book is to provide a text for teaching these fundamentals at a senior undergraduate or first-year graduate-level course. In the rest of Section 1.1 we describe the elements of the information networks, a brief history of major events since the inception of the industry, a summary of the important standards, and a short description of long-haul standards to interconnect networks worldwide. The rest of this chapter provides a more detailed overview of evolution of important wide-area networks

(WANs) and local-area networks (LANs) followed by a brief description of the material presented in the rest of this book.

1.1.1 Elements of Information Networks

Figure 1.1 illustrates the fundamental elements of information networking. A network infrastructure interconnects user applications through telecommunication devices using network adaptors to provide them with means for exchanging information. Users are human beings, computers, or "things" such as a light bulb. Applications could be a simple telephone call, sending a short message, downloading a file, or listening to audio or video streams. The telecommunication devices range from a simple dumb terminal only translating user's message to an electrical signal used for communication, up to a smart terminal enabling multiple applications through a number of networking options. The network adaptor could be a connector to a pair of wires for a plain old telephone, a cellular phone, or a wireless local network chip set for a personal computer, a laptop or a smartphone, a low-power personal communication chip set for a light bulb, or a reader for a smart card. The information network infrastructure consists of a number of interconnecting elements that are connected primarily through point-to-point links. Switches include fixed and variable-rate connection-based circuit switches or connectionless packet-switching routers. The point-to-point links include a variety of fibers, coaxial cables, twisted-pair wires, and wireless technologies.

Figure 1.2 shows a view of the evolution of telecommunication devices and the networking concepts which have allowed these devices to interconnect with one another. The first communication device was the Morse pad invented for telegraph application in the nineteenth century to transfer coded short messages using Morse code. This was followed by the telephones devices used for voice communications. Both terminals were dumb and used for human-to-human communications. Shortly after the Second World War, the first dumb computer terminals were networked to start the era of computer-to-computer and human-to-computer networking which finally emerged into the Internet. Simplicity, flexibility, and lower cost of implementation of Internet technology opened a new frontier for the emergence of numerous popular applications and computer networking devices.

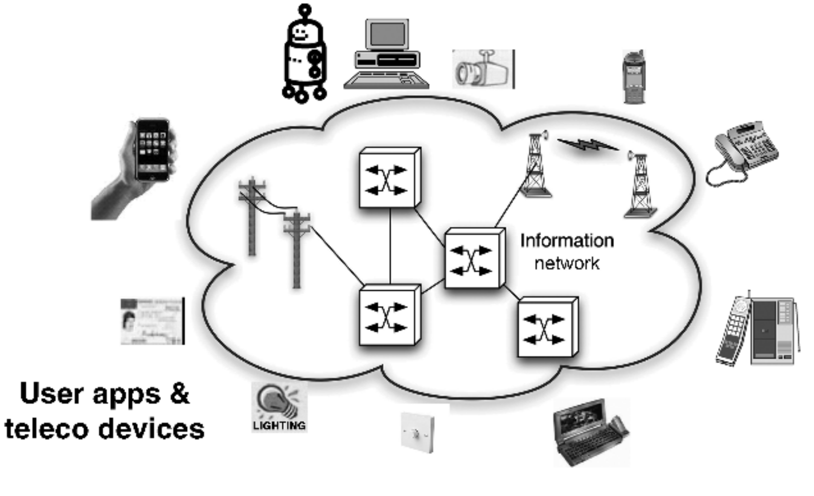

FIGURE 1.1 Elements of information networks.

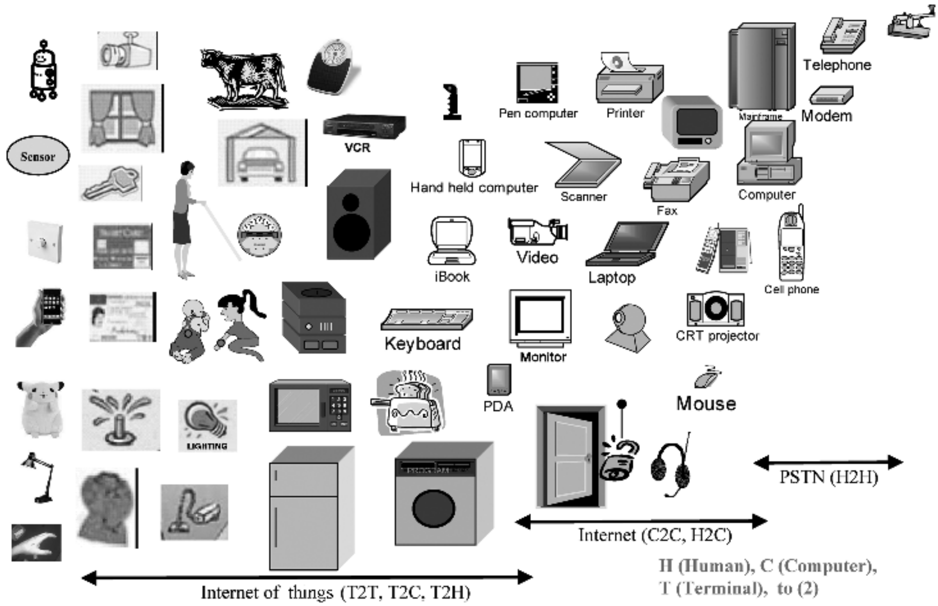

FIGURE 1.2 Evolution of telecommunication devices and information networks.

More recently, with the introduction of mobile wireless access to the PSTN and the Internet, a new window of opportunity for connecting “things” with the Internet and the so-called the “Internet of Things” has become popular. The Internet of Things allows things-to-human, things-to-computer and things-to-things networking, turning virtually everything to a communication device. Since these new devices have different data rates, power consumption, and cost requirements, a number of networking technologies have evolved in their support.

To support the evolution of telecommunication devices and applications, several information network infrastructures have evolved throughout the past 150 years. The largest of the existing backbone information networks are the PSTN, the Internet and the hybrid fiber cable (HFC). The PSTN was designed for the telephony application and it is also the backbone for popular cellular telephone networks. Cell phones are connecting to the PSTN using different cellular technologies. The Internet supports all computer communication data applications, and HFC was designed for cable TV distribution. To connect to the backbone networks, terminals are usually clustered in a local area to form a local network and the local network is connected to the backbone using another technology, which we can refer to as the access network. In this way, networking technologies are divided into core or backbone, access, and distribution or local networks.

In the PSTN industry, the local network is a private box exchange (PBX) used in office environments. It is a private switch allowing internal telephones of a company to talk with one another without the intervention of the core network. In the home, the local network for PSTN is the random tree wiring distribution in a residence which connects all rooms to the main line connected to the PSTN. Cordless telephones allow portable phones to connect to the home network. Cellular telephone companies add smaller base stations (BSs) called picocells inside large buildings, such as airports and shopping malls, and they are designing femtocell technologies for home applications to help cellular technologies to penetrate to indoor areas. In the case of the Internet, the local distribution network is a LAN. The Ethernet technology is dominating the wired LAN technology in offices, and WLANs complement them for mobile wireless access. In homes, the most popular Internet distribution network is the WLAN.

An access network is something between a WAN and a LAN. The infrastructure for the access network is a twisted-pair wire, a coaxial cable, a fiber line, a wireless terrestrial, or a satellite connection which connects the office or home to the backbone network. In the PSTN industry, this access network for the home is sometimes referred to as the last mile network. In the Internet industry it is sometimes referred to as metropolitan area networks (MANs). Home network access technologies are very important for the service providers because the high cost of the wiring to the home needs to be recuperated through the income of a single private subscriber.

1.1.2 Chronology of Information Networks

In the same way that the Greek philosophers of antiquity addressed the basic challenges in philosophy which laid the foundation for modern civilization, the emergence of the telegraph and the telephone in the early days of the information networking industry addressed the basic challenges facing information networking which have been carried on until modern times. Connection-based telephone conversations versus datagram-based connectionless messaging, digital versus analog, local versus wide area networking, wired versus wireless communications, and home versus office markets were all introduced in those early days. Over a century, engineers have discovered a number of technologies to enable these two services to adapt to the evolution of the terminals and to support ubiquitous operation.

To understand the sequence of events resulting in the evolution of information networks, it is useful to have a quick overview of the chronology of the events, which is presented in Table 1.1. Five years after Gauss and Weber's experiment to introduce wired telegraph for manually digitized data in 1834,[1] information networking started with the simple wired telegraph that used Morse code for digital data communication over long-distance wires between the two neighboring cities of Washington DC and Baltimore in 1839. It took 27 years, until 1866, for engineers to successfully extend this network over the ocean to make it a worldwide service. In 1900, 34 years after the challenging task of deploying cables in the ocean and 3 years after the first trial of the wireless telegraph, Marconi demonstrated *wireless* transoceanic telegraphy as the first wireless data application. It took over 150 years for this industry to grow into the wireless Internet. Bell started the telephone industry in 1867,[2] the first wired analog voice telecommunication service. It took 47 years for the telephone to become a transoceanic service in 1915, and it took almost 100 years for this industry to flourish into the wireless cellular telephone networks in the 1990s. The wireless telegraph was a point-to-point solution that eliminated the tedious task of laying very long wires in harsh environments. The telegraph was indeed a manual short messaging system (SMS) that

[1]Although focused on civil engineering, Rensselaer Polytechnic Institute (RPI), Troy, NY, the first engineering school in the USA, was established in 1824 as well. These events are indicators of the start of the industrial revolution and dominance of the engineers in shaping the future of the world.

[2]In the 1860s, in the dusts of the closing of the Civil War in the USA, a new wave of engineering and science schools mushroomed in the USA, starting with MIT (1862) in Boston and Worcester Polytechnic Institute (WPI; 1865) in Worcester, MA.

TABLE 1.1 A Brief History of Telecommunications

	Chronology of information networks
1839	First demonstration of telegraph between DC and Baltimore (Morse)
1876	Manually switched telephone for analog voice (Bell)
1900	Transoceanic wireless telegraph (Marconi)
1915	Transcontinental telephone (by Bell)
1946	First computer (U Penn)
1950	Voice-band modems for first computer networks using PSTN infrastructure
1968	Cable TV development and introduction of HFC
1969	ARPANET packet-switched network started (first node at UCLA)
1972	Demonstration of cellular systems (Motorola)
1973	Ethernet was invented (Metcalfe)
1980	IPv4 was released, fiber-optic systems were applied to the PSTN
1981	IEEE 802.3 adopted Ethernet
1986	IETF was formed
1990	GSM standard for TDMA cellular
1991	ATM Forum was founded
1994	Netscape was introduced and Internet became popular
1995	IS-95 standard for CDMA cellular, fast Ethernet at 100 Mb/s, first ATM specification
1996	IPv6 was defined by IETF
1997	IEEE 802.11 completed
1998	IEEE 802.1D MAC bridges and STA, gigabit Ethernet, 802.16 WMAN, IEEE 802.15.1 Bluetooth for WPAN
1999	IEEE 802.11b at 11 Mb/s
2000	3G IMT-2000 for wireless Internet access was introduced
2001	IEEE 802.11a for 54 Mb/s at 5 GHz using OFDM
2002	Mobile IP standard completed, UWB was used for high-speed WPAN
2003	IEEE 802.1Q virtual LAN, IEEE 802.11g using OFDM at 2.4 GHz, IEEE 802.15.4 ZigBee, 10 Gb/s Ethernet
2004	IEEE 802.1w rapid spanning tree algorithm for switches, IEEE 802.11d WiMAX for WMAN
2005	IEEE 802.11e mobile WiMAX
2006	RFID, sensor networks, "Internet of Things"
2007	IEEE 802.11n for 100 Mb/s
2008	iPhone, 100 Gb/s Ethernet

needed a skilled worker to decode the transmitted message. The wireless telephone network had to support numerous mobile users. While the challenge for wireless point-to-point communications is the design of the radio, the challenge for a wireless network is the design of a *system* that allows many mobile radios to work together.

The computer era started with the demonstration of the first digital computer at the University of Pennsylvania in 1946. Computers have revolutionized the traditional methods for information storage and processing that were in use since the dawn of literacy some 3000 years ago. The massive information stored and processed by computers needed communication networking. The first computer communication networks started after the Second World War by using voice-band modems operating over the PSTN infrastructure to exchange large amounts of data among computers located at great distances from one another. The need of the computer communication industry for massive information transfer and the high cost of leased lines provided by PSTN service providers to be used for voice-band data communications stimulated the evolution of sophisticated modem design technologies. By the late 1980s a number of modem design techniques were introduced which could achieve higher data rates over a fixed bandwidth channel [Pah88]]. These technologies laid the foundation for the design of the different physical layers that have been at the core of advancements in evolution of broadband access using cable modems and digital subscriber line (DSL), as well as LAN, WLAN, and WPAN technologies, in the 1990s and 2000s. In parallel with the growth of information theory to support higher data transmission rates, networking protocols emerged first for reliable transmission of data and later to facilitate the implementation of ever-growing computer applications.

About two decades after the emergence of circuit-switched computer communication networks, in 1969, the first wide-area packet-switched network called *Defense Advanced Research Projects Agency* Department Network (DARPAnet) was introduced, which later on became the Internet and gained popularity in the mid 1990s. A few years after the introduction of DARPAnet, in 1973, the first wired LAN, Ethernet, was invented, which dominated the LAN industry again in the mid 1990s. The Internet/Ethernet network core has dominated the networking industry, and numerous other technologies and applications have emerged around them. These technologies include a variety of Institute of Electrical and Electronics Engineers (IEEE) 802.11 WLANs, a number of IEEE 802.15 WPANs, several IEEE 802.16 wireless MANs (WMANs), a few IEEE 802.1 bridging technologies, and a number of transport control protocol (TCP)- and Internet protocol (IP)-based protocols defined by the Internet Engineering Task Force (IETF) which are highlighted in Table 1.1.

1.1.3 Standards Organizations for Information Networking

The increasing number of applications, and the information networking technologies to support them, has demanded standardization to facilitate the growth of the industry. Standards define specifications for the design of networks allowing multi-vendor operation which is essential for the growth of the industry. Figure 1.3 provides an overview of the standardization process in information networking. The standardization process starts in a special interest group of a standard developing body such as the IETF or IEEE 802.3, which defines the technical details of a networking technology as a standard for operation. The defined standard for implementation of the desired network is then moved for approval by a regional organization, such as the European Telecommunication Standards Institute

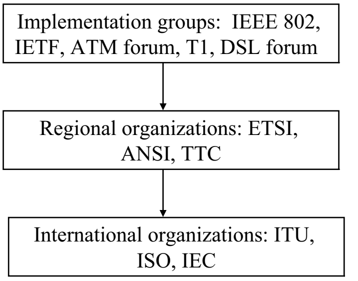

FIGURE 1.3 Standard development process.

TABLE 1.2 Summary of Important Standard Organizations for Information Networking

Important Standards Organizations	
IEEE (Institute of Electrical and Electronics Engineers)	Publishes 802 series standards for LANs and 802.11, 802.15, and 802.16 for wireless applications
T1	Sponsored by Alliance for Telecommunications Information Solutions (ATIS) telecommunication standards body working on North American standards
ATM (Asynchronous Transfer Mode) Forum	An industrial group working on a standard for ATM networks
DSL (Digital Subscriber Loop) Forum	An industrial group working on xDSL services
CableLab	Industrial alliance in the USA to certify DOCSIS-compatible cable modems
IETF (Internet Engineering Task Force)	Publishes Internet standards that include TCP/IP and SNMP. It is not an accredited standards organization
FCC (Federal Communication Commission)	The frequency administration authority in the USA.
EIA/TIA (Electronic/ Telecommunication Industry Association)	US national standard for North American wireless systems
ANSI (American National Standards Institute)	Accepted 802 series and forwarded to ISO. Also published FDDI, HIPPI, SCSI, and Fiber Channel. Developed JTC models for wireless channels
ETSI (European Telecommunication Standards Institute)	Published GSM, HIPERLAN/1, and UMTS
CEPT (Committee of the European Post and Telecommunication)	Standardization body of the European Posts Telegraph and Telephone (PTT) ministries. Co-published GSM with ETSI
IEC (International Electrotechnical Commission)	Publishes jointly with ISO
ISO (International Standards Organization)	Ultimate international authority for approval of standards
ITU (International Telecommunication Union formerly CCITT)	International advisory committee under United Nations. The Telecommunication Sector, UTU-T, published ISDN and wide-area ATM standards. Also works on IMT-2000

(ETSI) or the American National Standards Institute (ANSI). The regional recommendation is finally submitted to world-level organizations, such as the International Telecommunications Union (ITU), International Standards Organization (ISO), or International Electrotechnical Commission (IEC), for final approval as an international standard. There are a number of standards organizations involved in information networking. Table 1.2 provides a summary of the important standards playing major roles in shaping the information networking industry which are also mentioned in this book.

The most important of the standard development organizations for technologies described in this book produces the IEEE 802-series standards for personal, local, and metropolitan area networking. The IEEE, the largest engineering organization in the world, publishes a number of technical journals and magazines and organizes numerous conferences worldwide. The IEEE 802 community is involved in defining standard specifications for information networks. The number 802 was simply the next free number that the IEEE could assign to a committee at the inception of the group on February 1980, although "80-2" is sometimes associated with the date of the first meeting. Regardless of the ambiguity of the name, the IEEE 802 community has played a major role in the evolution of information networks by introducing IEEE 802.3 Ethernet, IEEE 802.11 WLANs, IEEE 802.15 WPAN, and IEEE 802.16 WMAN and other standards which are discussed in detail in this book.

Another important standard development organization is the IETF, which was established in January 1986 to develop and promote Internet standard protocols around the TCP/IP suite for a variety of popular applications. In the 1990s, the Asynchronous Transfer Mode (ATM) Forum was an important standard development group trying to develop standards for connection-based fixed packet-length communications for the integration of all services. This philosophy was in contrast with Internet/Ethernet networking using connectionless communications with variable and long-length packets.

Telecommunication/Electronic Industry Association (TIA/EIA) is a US national standards body defining a variety of wire specifications used in LANs, MANs, and WANs. The TIA/EIA are trade associations in the USA representing several hundred telecommunications companies. The TIA/EIA has cooperated with the IEEE 802 community to define the media for most of the wired LANs used in fast and gigabit Ethernet. TIA/EIA also defines cellular telephone standards such as Interim Standard (IS-95) or cdmaOne and the IS-2000 or CDMA-2000 (respectively the second and third generation) cellular networks. ETSI and the Committee of the European Post and Telecommunications (CEPT) were the European standardization bodies publishing wireless networking standards, such as the global system for mobile communications (GSM) and the universal mobile telecommunications system (UMTS), in the EU.

The most important international standards organizations are the ITU, the ISO, and the IEC, which are all based in Geneva, Switzerland. Established in 1865, the ITU is an international advisory committee under the United Nations and its main charter includes telecommunication standardization and allocation of the radio spectrum. The telecommunication sector, ITU-T, has published for instance the integrated service data network (ISDN) and wide-area ATM standards, as well as International Mobile Telephone (IMT-2000) for 3G cellular networks. The World Administrative Radio Conference (WARC) was a technical conference of the ITU where delegates from member nations of the ITU met to revise or amend the entire international radio regulations pertaining to all telecommunication services throughout the world. The ISO and IEC are composed of the national standards bodies, one per member economy. These two standards often work with one another as the ultimate world standard organization. Established in 1947, the ISO nurtures worldwide proprietary industrial and commercial standards that often become law, either through treaties or national standards. The ISO seven-layer model for computer networking is one of the prominent examples of ISO standards. IEC, which started in 1906, is a nongovernmental international standards organization for "electrotechnology," which includes a vast number of standards from power generation, transmission and distribution to home appliances and office equipment, to telecommunication standards. The IEC publishes standards with the IEEE and develops standards jointly with the ISO and the ITU.

1.1.4 Evolution of Long-Haul Multiplexing Standards

In telecommunications and computer networks, multiplexing is used where multiple data streams are combined into one signal to share the expensive long-haul transmission resources. From a different perspective, multiplexing divides the physical capacity of the transmission medium into several logical channels, each carrying a data stream. The two most basic forms of multiplexing over point-to-point connections are time-division multiplexing (TDM) and frequency-division multiplexing (FDM). In optical communications, FDM is referred to as wavelength-division multiplexing (WDM). Multiple streams of digital data can also use code-division multiplexing (CDM), which has not been commercially successful over wired networks. Variable bit-rate digital bit streams may be transferred efficiently over a fixed-bandwidth channel similar to TDM by means of statistical multiplexing techniques such as ATM. If multiplexing is used for channel access then it is referred to as medium access control (MAC), in which case TDM becomes time-division multiple access (TDMA), FDM becomes frequency-division multiple access (FDMA), CDM becomes code-division multiple access (CDMA), and statistical multiplexing into something like carrier sense multiple access (CSMA). Multiplexing techniques are simple and they are part of the physical layer of the network. We discuss them in this section. MAC protocols are more complex and we describe them in Chapter 5.

In PSTN, the home user's telephone line carrying telephone or DSL data typically ends at the remote concentrator boxes distributed in the streets, where these lines are multiplexed and carried to the central switching office on significantly fewer numbers of wires and for much further distances than a customer's line can practically go. Fiber multiplexing lines, mostly using ATM protocols, are commonly used as the backbone of the network which connects POTS lines with the rest of the PSTN and carry data provided by DSLs. As a result, PSTN has been the driver for the development and standardization of most multiplexing techniques. In the early 1960s, the first multiplexing system used for telephony was FDM. Figure 1.4 illustrates this early multiplexing system. This system multiplexed 12 subscribers, each with a 4 kHz bandwidth signal in frequencies between 60 and 108 kHz. Figure 1.4 shows the original bandwidths for each subscriber, the bandwidths raised in frequency, and the multiplexed channel. In PSTN connection to the home, as shown in Figure 1.5, FDM is also used to multiplex DSL data services with POTS and the so called Home Phone Network Alliance (HPNA) signal for Ethernet-like networking over home telephone wires. The POTSs use the frequency range between 20 Hz and 3.4 kHz, DSL uses

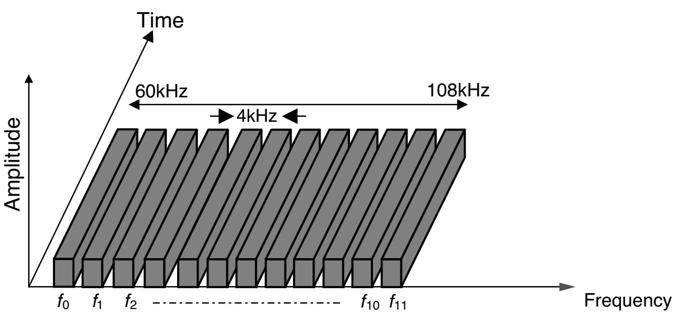

FIGURE 1.4 FDM used in telephone networks multiplexing 12 subscribers each with 4 kHz bandwidth in frequencies between 60–108 kHz.

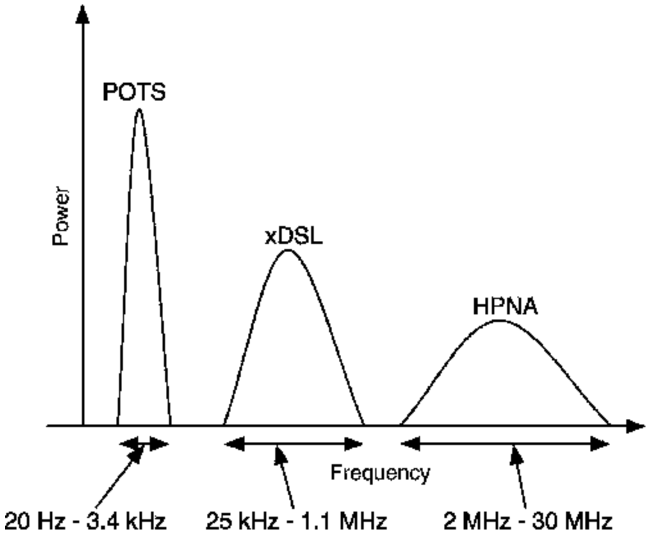

FIGURE 1.5 Phone line wirings shared among three technologies using FDM.

between 25 kHz and 1.1 MHz, and HPNA uses between 2 and 30 MHz. The TV signals for black and white content, color, and audio are also frequency-division multiplexed. The analog cable TV channels are also separated using FDM.

The first TDM system was developed for telephony application as well. This system carried 24 PCM-encoded digitized voice calls, each 64 kb/s, over four-wire copper lines at a rate of 1.544 Mb/s. Figure 1.6 shows the 193-bit frame used in a T1-carrier: there are 8 bits per channel for $24 \times 8 = 192$ bits and a single bit known as the frame bit. Each 8 bits consists of 7 bits representing a sample of the voice and 1 bit for control signaling. Each frame is transmitted in 125 ms to support a bit rate of 8 (bits)/125 (ms) = 64 kb/s per channel and an effective data rate of 7 (bits)/125 (ms) = 56 kb/s. The remaining 8 kb/s is used to carry the signaling information to set up telephone calls. A T1-carrier has a higher layer hierarchy to support higher data rates. Figure 1.7 shows the T-carrier hierarchy: every four T1 carriers result in a T2 carrier with the rate of 6.312 Mb/s, each seven T2 carriers form a T3 carrier which carries 44.736 Mb/s, and six T3 carriers form a T4 carrier at 274.176 Mb/s. Although the Japanese followed the American carrier system, the Europeans later developed their

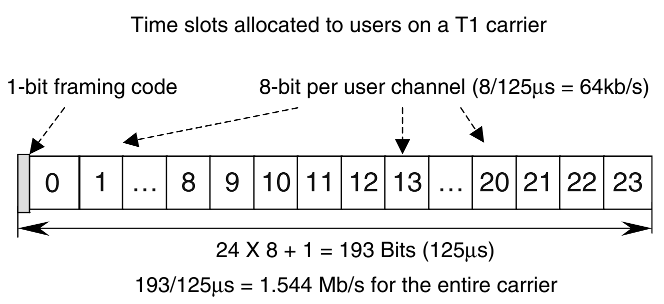

FIGURE 1.6 T1 carrier for multiplexing 24 digitized voice signals each carrying 64 kb/s for a total 1.544 Mb/s.

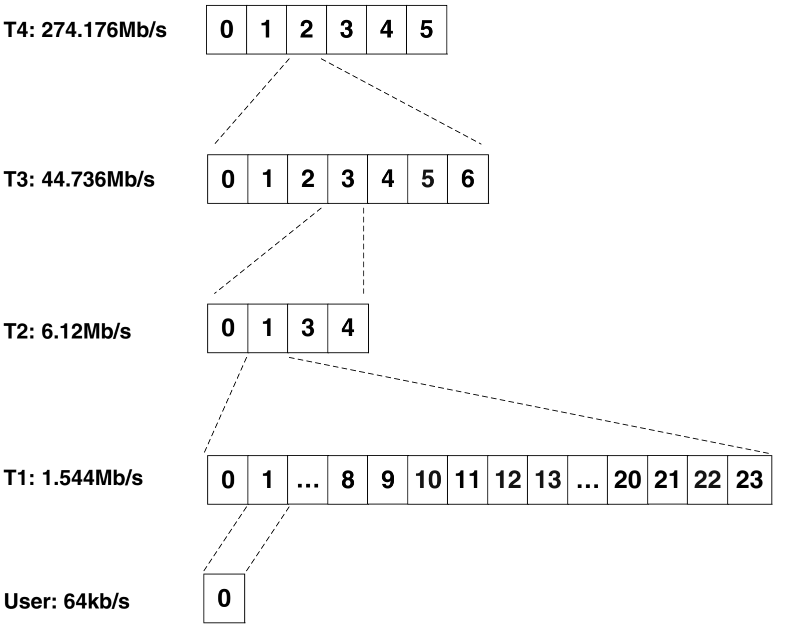

FIGURE 1.7 The legacy T-carrier hierarchy for long-haul TDM transmission of PSTN voice streams in the USA and Japan.

own TDM hierarchy for telephony which combines 30 channels rather than 24 channels to form the basic stream. The next three layers of hierarchy in the European system each are four times larger than the previous level.

With the popularity of optical communications in the 1980s and their ability to support much higher transmission rates, there was a need to extend the existing TDM hierarchies. At the same time, AT&T was broken up and there was a need to develop a standard TDM hierarchy so that the multivendor manufactured devices for different companies could cooperate with one another. In this setting, the synchronous optical network (SONET) hierarchy started in North America. Later on the ITU became involved and the name synchronous digital hierarchy (SDH) was selected as the name of the standard (which has only minor differences with SONET). The SONET/SDH hierarchy defines a common signaling standard for multivendor operation (for wavelength, timing, and frame structure), unifies the US, the EU, and Japanese standards, defines data rates higher than T-carriers, and provides for support of operation, administration, and maintenance (OAM) of the network. SONET/SDH can be used for encapsulation of earlier digital transmission standards and they can be directly used to support ATM or SONET/SDH packet mode of operation providing for generic and all-purpose transport containers for multimedia information.

In a manner similar to the T1 carrier, the overhead and the payload of the SONET streams are interleaved and all frames take 125 ms. Here, the basic frame, called the synchronous transport signal1 (STS-1)[3] or optical carrier1 (OC-1), is 810 octets in size and the frame is transmitted with three octets of delimiter indicating the start of the frame followed by nine 87 octets of payload each having three octets of overhead, followed by 84 octets of user data.

[3]This is the name for the electrical rather than optical signal.

TABLE 1.3 SONET/SDH Hierarchy of Data Rates and Frame Format

SONET optical	SONET electrical	SDH level electrical	Payload bandwidth (kb/s)	Line rate (kb/s)
OC-1	STS-1	STM-0	48 960	51 840
OC-3	STS-3	STM-1	150 336	155 520
OC-12	STS-12	STM-4	601 344	622 080
OC-24	STS-24	STM-8	1 202 688	1 244 160
OC-48	STS-48	STM-16	2 405 376	2 488 320
OC-96	STS-96	STM-32	4 810 752	4 976 640
OC-192	STS-192	STM-64	9 621 504	9 953 280
OC-768	STS-768	STM-256	38 486 016	39 813 120
OC-1536	STS-1536	STM-512	76 972 032	79 626 120
OC-3072	STS-3072	STM-1024	153 944 064	159 252 240

If we align all 87 rows then we have a block of 9×87 octets of payload in which the first three overhead columns appear as a contiguous block, as do the remaining 84 columns of user data. With this format, if we extract one octet from the bitstream every 125 ms duration of a frame, this gives a data rate of 8 (bits)/125 (ms) = 64 kb/s representing a telephone user. This is very useful for fast switching of low-speed streams embedded in extremely high data streams without any need to understand or decode the entire frame. The basic frame in SDH is called synchronous transport mode1 (STM-1) which has similar properties to OC-1/STS-1 with minor differences. These simple formats allow design of relatively simple devices to take a SDH data for a specific user and insert that in a SONET stream. This simple structure allows implementation of faster switches operating at higher data rates. Again, like the T1 hierarchy, SONET and SDH have their own TDM hierarchy, which is shown in Table 1.3.

1.2 EVOLUTION OF WIDE-AREA NETWORKS

The information sources carried through the information networks are divided into voice, data, and video. The most commonly used wired infrastructures to carry voice, data, and video are the PSTN, Internet, and HFC respectively. The dominant voice application is telephony that is a bidirectional symmetric real-time conversation. To support telephony, telephone service providers have developed a worldwide network infrastructure that establishes a connection for a telephone call during the dialing process and disconnects it after completion of the conversation. This network, commonly referred to as PSTN, is connection based using circuit switching and it has the capability of assuring a certain quality of service (QoS) to the user during the connection time. The core of the PSTN is a huge digital transmission system that allocates a 64 kb/s circuit for each direction of a telephone conversation. Other network providers, to interconnect their nodes, often lease the PSTN transmission facilities (e.g. making use of the long-haul standards described in the previous section). The Internet is a connectionless worldwide public data network (PDN) using packet switching and the standard IP. The Internet is a “network of networks” that consists of numerous academic, business, and government networks, which together carry various information and services, such as e-mail, web access, file transfer, and many other emerging applications. HFC is the infrastructure developed for video applications in cable TV. This network broadcasts wideband video signals to residential buildings. A cable goes from an end office to a residential area and all users tap their signals from the same cable. The set-top boxes leased by cable companies provide selectivity of channels depending on the rates charged. The end offices, where a group of distribution cables arrive, are connected to one another through a fiber line. For this reason, the cable TV network is also called HFC. Cable distribution is also now used for broadband home access to the Internet.

1.2.1 Evolution of the Public Switched Telephone Network

The invention of the telephone in 1876 was the start of analog telephone networking and the PSTN. In the early days, networks used operators to switch or route a session from one terminal to another manually. At the beginning of the twentieth century the telecommunications industry had already been exposed to a number important issues that played different roles during the entire course of the past century, culminating in the emergence of modern wireless networks. Among these important issues were analog versus digital, voice versus data, wireless versus wired, local versus long-haul communications, and personal versus group services. By the 1950s, the PSTN had more than 10 million customers in the USA, and those interested in long-haul communication issues also needed their services to solve their problems. Although end users are still mostly connected to the PSTN with twisted-pair analog lines, to provide flexibility and ease of maintenance and operation of the PSTN, the core network gradually changed to digital switches and digital wired lines connecting switches together. A hierarchy of digital lines (the T-carriers in the USA described previously) evolved as trunks to connect switches of different sizes together.

Another advancement in the PSTN was the development of private branch exchanges (PBXs) as privately owned local telephone networks for large offices. A PBX is a voice-oriented LAN owned by the end organization itself, rather than the telephone service provider. This small switch allows the telephone company to reduce the number of wires that are needed to connect all the lines in an office to the local office of the PSTN. In this way, the service provider reduces the number of wires to be laid to a small area where large offices with many subscribers are located. The end user also pays less to the telephone company. The organization thus has an opportunity to enhance services to the end users connected to the PBX.

In the 1920s, Bell Laboratories conducted studies to use the PSTN facilities for data communications. In this experiment, the possibility of using analog telephone lines for transferring transoceanic telegrams was examined. Researchers involved in this project discovered several key issues, including the sampling theorem and the effects of phase distortion on digital communications. However, these discoveries did not affect applications until after the Second World War, when Bell Laboratories developed voice-band modems for communication among air force computers in air bases that were geographically separated by large distances [Pah88]. These modems soon found their way into commercial airlines and banking industries, resulting in associated private long-haul data networks. These pioneering computer communications networks consisted of a central computer and a bank of modems operating over four-wire commercial-grade leased telephone lines to connect several terminals to the computer. In the late 1960s, the highest data rate for commercial modems was 4800 bits/s. By the early 1970s, with the invention of quadrature amplitude modulation (QAM), the data rate of four-wire voice-band modems reached 9600 bits/s. In the early 1980s, trellis-coded modulation (TCM) was invented, which increased data rates to 19.2 kb/s and beyond.

In parallel with the commercial four-wire modems used in early long haul computer networks, two-wire modems emerged for distance connection of computer terminals. The two-wire modems operated over standard two-wire telephone lines and they were equipped with dialing procedures to initiate a call and establish a POTS line during the session. These modems started at data rates of 300 bits/s. By the early 1970s, they had reached 1200 bits/s, and by the mid 1980s they were running at 9600 bits/s. These two-wire voice-band modems allowed users in the home and office to have access to regular telephones to develop a data link connection with a distant modem also having access to the PSTN. Voice-band modems using two-wire telephone connections soon found a large market in the residential and small office remote computer access (Telnet), and the technology soon spread to a number of popular applications, such as operating a facsimile machine or credit card verification device. With the popularity of Internet access, a new gold rush for higher speed modems began, resulting in 33.6 kb/s full-duplex modems in 1995 and 56 kb/s asymmetric modems by 1998. The 56 kb/s modems use dialing procedures and operate within the 4 kHz voice-band, but they connect directly to the core PCM digital network of the PSTN that is similar to DSLs. DSLs use the frequency band between 2.4 kHz and 1.1 MHz to support data rates up to 10 Mb/s over two-wire telephone lines.

More recently, cellular telephone services have evolved. To connect a cellular telephone to the PSTN, the cellular operators developed their own infrastructure to support mobility. This infrastructure was connected to the PSTN to allow mobile to fixed telephone conversations. Addition of new services to the PSTN demanded increases in the intelligence of the core network to support these services. As this intelligence advanced, the telephone service provider added value features such as voice mail, autodialing through network operators, call forwarding, and caller identification to the basic POTS traditionally supported.

1.2.2 Emergence of the Internet

Public data networks (PDNs) that evolved around voice-band modems connected a variety of applications in a semi-private manner. The core of the network was still the PSTN, but the application was for specific corporate use and was not offered privately to individual users. These networks were private data networks designed for specific applications and they did not have standard transport protocols to allow them to interconnect with one another. Another irony of this operation was that the digital data was first converted to analog to be transmitted over the telephone network and then, within the telephone network, it was again converted to digital format for transmission over long distances using the digital subcarrier system. To avoid this situation, starting in mid 1970s, telephone companies started to introduce digital data services (DDSs) that provided a 56 kb/s digital service directly delivered to the end user. The idea was great because, at that time, the maximum data rate for voice-band modems was 9600 bits/s. However, like many other good and new ideas in telecommunications, this idea did not become popular. A large amount of capital was already invested in the existing voice-band-based data networks and it was not practical to replace them at once and DDSs were not interoperable with the analog modems. The DDSs later emerged as ISDN services providing 2×64 kb/s voice channels and 1×16 kb/s data channel to individual users. Penetration rates of ISDN services were not as expected, but laid a foundation for digital cellular services. Digital cellular systems can be viewed as a sort of wireless ISDN technology that integrates basic digital voice with a number of data services at the terminal.

The major cost for operation of a computer network over the four-wire lines was the cost of leasing lines from the telephone company. To reduce the operation cost, multiplexers were used to connect several lower speed modems and carry all of them at once over a higher speed modem operating over a long-distance line. The next generation of multiplexers consisted of statistical multiplexers that multiplexed flows of data rather than multiplexing individual modem connections. Statistical multiplexing technology later evolved into router technology that is generalized packet data switching.

In the early 1970s, the rapid increase in the number of terminals in offices and manufacturing floors was the force behind the emergence of LANs. These LANs provided high-speed connections (greater than 1 Mb/s) among terminals, facilitating sharing printers or mainframes from different locations. LANs were providing a local medium specifically designed for data communications that was completely independent from the PSTN. By the mid 1980s, several successful LAN topologies and protocols were standardized and LANs were installed in most large offices and manufacturing floors connecting their computing facilities. However, the income of the data communication industry, both LANs and PDNs, was far below that of the PSTN, still leaving the PSTN as the dominant economical force in the information networking industry.

Another important and innovative event in 1970s was the implementation of ARPANET, the first packet-switched data network connecting 50 cities in the USA. This experimental network used routers rather than the PSTN switches to interconnect data terminals. The routers were originally connected via 56 kb/s digital leased lines from the telephone company and the ARPANET interconnected several universities and government computers around a large geographical area. This network was the first packet-switched network supporting end-to-end digital services. This basic network later on upgraded to higher speed lines and numerous additional networks. To facilitate a uniform communication protocol to interconnect these disparate networks, TCP/IP protocols evolved that allowed LANs and a number of other PDNs to interconnect with one another and form the Internet. In the mid 1990s, with the introduction of popular applications such as Telnet, file transfer protocol (FTP), e-mail, and web browsing, the Internet industry was created. Soon, the Internet penetrated the home market and the number of Internet users became comparable with that of the PSTN, creating another economical power, namely computer communications applications, that compete with the traditional PSTN. The IP-based Internet provides a cheaper solution than circuit-switched operations, and today people are thinking of employing IP to capture a large share of the traditional telephony market served by the PSTN. The Internet provides a much lower cost alternative to PSTN for support of multimedia applications. With the growth of the wireless industry in the past two decades (WLANs and wireless wide-area data networks), wireless access to the Internet has become very popular.

In a manner similar to cellular telephony, wireless data network infrastructures have evolved around the existing wired data network infrastructures. WLANs are designed mostly for in-building applications to cover a small area and the network has a minimal infrastructure. WLANs are usually connected to the existing wired LANs as an extension. Mobile data services are designed for lower speed wireless data applications with metropolitan, national, and global coverage.

1.2.3 HFC Infrastructure for Cable TV

Another competing wired infrastructure that evolved in the last few decades of the twentieth century was the cable TV network. Installation of cable TV distribution networks in the USA started in 1968 and has penetrated more than 60% of the residential homes in the USA. This penetration rate is getting close to that of the PSTN. The cable TV network consists of three basic elements: a regional hub, a distribution cable bus, and a fiber ring to connect the hubs to one another. Because of the hybrid usage of fiber and cable, this network is also referred to as an HFC network, as mentioned earlier. The signals containing all channels at the hub are distributed through the cable bus in a residential area and each home taps the signal off the bus. This is radically different from home access through twisted-pair wires provided by the PSTN in many ways. The bandwidth of the coaxial cable supports about 100 TV channels, each around 6 MHz, while the telephone basic channel is around 4 kHz. The extended telephone channel using DSL uses about 1 MHz of bandwidth. The cable access is via a long bus originally designed for one-way multicast that has a number of taps (up to 500) creating a less controllable medium. The twisted-pair star access for the PSTN is designed for two-way operation and is easier to control. The HFC channel is noisier than the telephone channel, and in spite of its wider bandwidth its current supported broadband data rates are of the same range as the xDSL services operating on telephone wirings.

The cable TV network was also considered as a backbone for cellular telephone systems and it is considered as the leading method for broadband home access to support evolving home networks. Some of the cable TV providers in the USA also offer telephone services over this medium. In the late 1990s, the success of cable in broadband access encouraged some of the PSTN providers, such as AT&T, to acquire cable companies, such as MediaOne. With the introduction of fiber to home services with integrated high-speed internet access, telephony, and TV services, the cable TV industry is experiencing challenges from traditional PSTN companies that are providing fiber to home services.

1.2.4 Evolution of Cellular Telephone Networks

The technology for the first-generation (1G) FDMA analog cellular systems was developed at AT&T Bell Laboratories in the early 1970s. However, the first deployment of these systems took place in the Nordic countries under the name Nordic Mobile Telephone (NMT) about a year earlier than the deployment of the Advanced Mobile Phone Services (AMPS) in the USA. Since the USA is a large country, the frequency administration process was slower and so it took a longer time for deployment. The second-generation (2G) digital cellular networks started in the Nordic countries with the formation of the GSM standardization group. The GSM standard group was originally formed to address international roaming, a serious problem for cellular operation in the EU countries. The standardization group quickly decided to go for a new digital TDMA technology because it could allow integration of other services to expand the horizon of wireless applications [HAU94]. In the USA, however, the reason for migration to digital cellular was that the capacity of the analog systems in major metropolitan areas such as New York City and Los Angles had reached its peak value and there was a need for increasing the capacity in the existing allocated bands. Although the Nordic countries, led by Finland, have always maintained the highest rate of cellular penetration, in the early days of this industry the USA was by far the largest market. By 1994, there were 41 million subscribers worldwide, 25 million of them in the USA. The need for higher capacity motivated the study of CDMA that was originally perceived to provide a capacity that was orders of magnitude higher than other alternatives, such as analog band splitting or digital TDMA.

While the debate between TDMA and CDMA for 2G was in progress in the USA, deployment of GSM technology started in the EU in the early 1990s. At the same time, developing countries started their planning for cellular telephone networks and most of them adopted the GSM digital cellular technology over legacy analog cellular systems. Soon afterwards, GSM had penetrated into more than 100 different countries. An interesting phenomenon in the evolution of the cellular telephone industry was the unexpected rapid expansion of this industry in developing countries. In these countries, the growth of the infrastructure for wired POTS was slower than the growth of the demand for the new subscriptions, and always there were long waiting times to acquire a telephone line. As a result, in most of these countries, telephone subscriptions were sold in the black market at a price several times their actual value. Penetration of the cellular telephone in these counties was much easier because people were already prepared for higher prices for telephone subscription. Also, deployment and expansion of cellular networks could be done much faster than POTS.

In the beginning of the race between TDMA and CDMA, CDMA technology was deployed only in a few countries. Moreover, experimentation had shown that the capacity improvement factor of CDMA was smaller than expected. In the mid 1990s, when the first deployments of CDMA technology started in the USA, most companies were subsidizing the cost to stay in race with the TDMA and analog alternatives. However, from day one, the quality of voice using CDMA was superior to that of TDMA systems installed in the USA. As a result, CDMA service providers under banners like "you cannot believe your ears" started marketing this technology in the USA that soon become very popular with the users. Meanwhile, with the huge success of digital cellular, all manufacturers worldwide started working on the 3G international mobile telephone (IMT-2000) wireless networks.

The purpose of migration to 3G networks was to develop an international standard that combines and gradually replaces 2G digital cellular. At the same time, 3G systems were expected to increase the quality of the voice, capacity of the network, and data rate of mobile data services. Among several radio transmission technology proposals submitted to the ITU, the dominant technology for 3G systems was wideband CDMA (W-CDMA) that is discussed in Chapter 7.

1.3 EVOLUTION OF LOCAL NETWORKS

Outside of the of the PSTN, Internet, HFC, and cellular WANs, the PBX, LAN, WLAN and WPAN technologies are used as local networks to distribute the network services inside an office or at home. The cost of infrastructure in WANs is very high and the coverage is very wide. As a result, WANs are offered as a charged *service* to the user. The service provider invests a large capital for the installation of the infrastructure and generates revenue through monthly service charges. Local networks are often sold as end products to the user and there is no service payment for local communications. PBX networks are owned by the companies for their local communications. The only time that a company owning a PBX pays the PSTN service provider is when a call goes out of the local area using the service provider's infrastructure. Operations of LANs, WLANs, and WPANs are very similar to a PBX, in that the user owns them and pays monthly charges to the wide area Internet service providers for wide area communications.

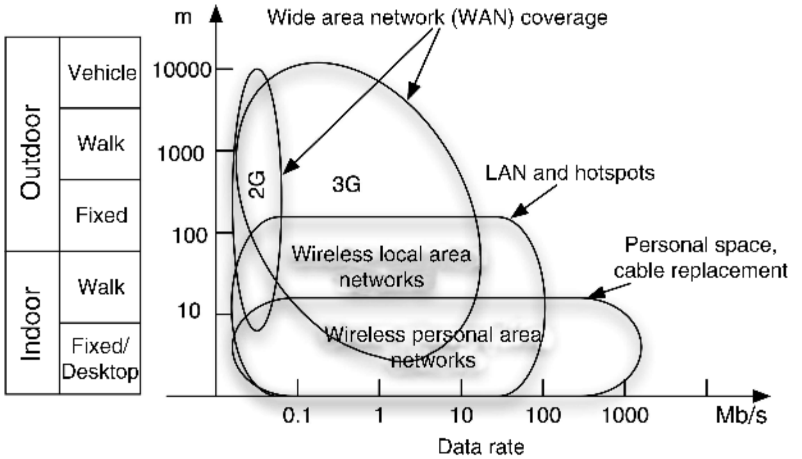

FIGURE 1.8 Relative coverage and data rates of different technologies.

Numerous local network standards and products have evolved around the PSTN and the Internet. To connect to the PSTN, first we had PBX systems and then cordless telephone and personal communication services (PCSs). Standards and products developed in these domains were either simple or they did not gain vast commercial success. As a result, we do not address their technical details in this book; details of more technically challenging wireless PCS standards and products are available in [Pah95, Pah02]. In wired data networking, users connect to the Internet through a LAN. In the past four decades, a number of wired LAN technologies have emerged in the market and the IEEE 802.3 Ethernet has survived as the technology of choice. Again, technologies such as token ring and fiber distributed data interface are not considered in this book; the reader can refer to books such as *Local and Metropolitan Area Networks* [Sta00] for details of these standards. In wireless data networks, the user can either connect directly to the Internet through a lower speed cell phone with universal coverage or can connect through a higher speed WLAN or WPAN that has a limited coverage. Figure 1.8 illustrates the relative coverage and data rates of 2G, 3G, WLAN, and WPAN technologies. In the remainder of this section we provide an overview of the evolution of the local access to the PSTN, IEEE 802.3 Ethernet, IEEE 802.11 WLAN, and the IEEE 802.11 WLANs.

1.3.1 Evolution of Local Access to Public Switched Telephone Network

Connection-based wired local networks were PBX systems which became popular after the Second World War for office applications. Every office in a large organization still has a PBX telephone branch, but it is not used as often as before. Cell phones are more common for voice applications and e-mails/instant messaging are replacing a number of office telephone applications. In large homes, people sometimes use intercoms for connection-based local communications. In the mid 1990s, when most people in the telecommunication industry believed that ATM would take over the entire emerging multimedia communications industry, ATM LAN emulation (LANE) was initiated. The purpose of ATM-LANE was to adapt the existing legacy LAN infrastructures and applications to the then perceived end-to-end ATM network. The main technical challenge in implementing LANE was the adaptation of a connectionless legacy LAN into a connection-oriented ATM network. This technology never gained commercial importance or acceptance.

Local wireless telephone applications started with the introduction of the cordless telephone that appeared in the market in the late 1970s. A cordless telephone provides a wireless connection to replace the wire between the handset and the telephone set. The technology for implementation of a cordless telephone was similar to the technology used in walkie-talkies that had existed since the Second World War. The important feature of the cordless telephone was that as soon as it was introduced in the market it became a major commercial success, selling on the order of tens of millions and generating an income exceeding several billions of dollars.

The success of the cordless telephone encouraged further developments in this field. The first digital cordless telephone was cordless telephone-2 (CT-2), a standard developed in the UK in the early 1980s. The next generation of cordless telephones was wireless PBX using the digital European cordless telephone (DECT) standard. Both CT-2 and DECT had minimal network infrastructures to go beyond the simple cordless telephone paradigm and perhaps cover a larger area and multiple applications. However, in spite of the huge success of the cordless telephone, neither CT-2 nor DECT are considered commercially successful systems. These local systems soon evolved into PCSs that consisted of a complete system with their own infrastructure, very similar to cellular mobile telephone systems.

In the technical communities of the early 1990s, PCSs were differentiated from the cellular systems. A PCS service was considered "personal" and as the next-generation cordless telephone designed for residential areas, providing a variety of services beyond the cordless telephone. The first real deployment of a PCS system was the personal handy phone (PHP), later renamed the personal handy system (PHS), introduced in Japan in 1993. At that time, the technical difference between PCS services and cellular systems was perceived to be smaller cell size, better quality of speech, lower tariff, less power consumption, and lower mobility. However, from the user's point of view, the terminals and services for PCS and cellular looked very similar and the only significant difference was marketing strategy and the way that they were introduced to the market. For instance, around the same time, in the UK, DEC-1800 services were introduced as a PCS service. DEC-1800 was using GSM technology at a higher frequency of 1800 MHz, but it employed a different marketing strategy. The last PCS standard was PACS in the USA, finalized in 1995. All together, none of the PCS standards became a major commercial success or a competitor to cellular services.

In 1995, the Federal Communication Commission (FCC) in the USA auctioned the frequency bands around 2 GHz as the PCS bands, but PCS-specific standards were not adopted for these frequencies. Eventually, the name PCS started to appear only as a marketing pitch by some service providers for digital cellular services, in some cases not even operating in the PCS bands. While the more advanced and complex PCS services evolving from simple cordless telephone applications did not succeed and merged into the cellular telephone industry, the simple cordless telephone industry itself still remains active. In more recent years, the frequency of operation of cordless telephone products has shifted into unlicensed industrial, scientific, and medical (ISM) bands rather than the licensed PCS bands. Cordless telephones in the ISM bands can provide a more reliable link using spread spectrum technology. More recently, Voice-over-IP (VoIP) phones have been introduced in the market which use WLANs in the home. Femtocell technology is emerging for local home applications to integrate wireless local data and cellular telephone applications.

1.3.2 Evolution of the IEEE 802.3 Ethernet

The LAN industry emerged during the 1970s to enable sharing of expensive resources like printers and to manage the wiring problem caused by the increasing number of terminals in offices. By the early 1980s, three standards were developed: Ethernet (IEEE 802.3), token bus (IEEE 802.4) and token ring (IEEE 802.5), specifying three distinct PHY and MAC layers and different topologies for networking over the thick cable medium but sharing the same management and bridging (IEEE 802.1) and logical link control (LLC) layers. With the growing popularity of LANs in the mid 1980s, the high installation costs of thick cable in office buildings moved the LAN industry toward using thin cables, which is also referred to as "cheapernet." Cheapernet covered shorter distances of up to 185 m, compared with the 500 m coverage of thick cables. In the early 1990s, the star topology (often referred to as hub-and-spoke LANs) using easy-to-wire twisted-pair wiring with coverage of 100 m was introduced. Figure 1.9 depicts the evolution of the Ethernet wired LAN from thick to thin and finally twisted-pair networks. The interesting observation is that this industry has made a compromise on the coverage to obtain a more structured solution that is also easier to install. Twisted-pair wiring, also used by PSTN service providers for telephone wiring distribution in homes and offices for over 100 years, is much easier to install. The star network topology opened an avenue for structured hierarchical wiring, also similar to the telephone network topology. Today, IEEE 802.3 (Ethernet) using twisted-pair wiring is the dominant wired LAN technology.

The data rates of legacy LANs (thick, thin, and twisted-pair) were all 10 Mb/s. The need for higher data rates emerged from two directions: (1) there was a need to interconnect LANs located in different buildings oo a campus to share high-speed servers; (2) computer terminals became faster and capable of running high-speed multimedia applications. To address these needs, several standards for higher data rate operations were introduced. The first fast LAN operating at 100 Mb/s was the fiber distributed data interface (FDDI) that emerged in the mid 1980s as a backbone medium for interconnecting LANs. The ANSI

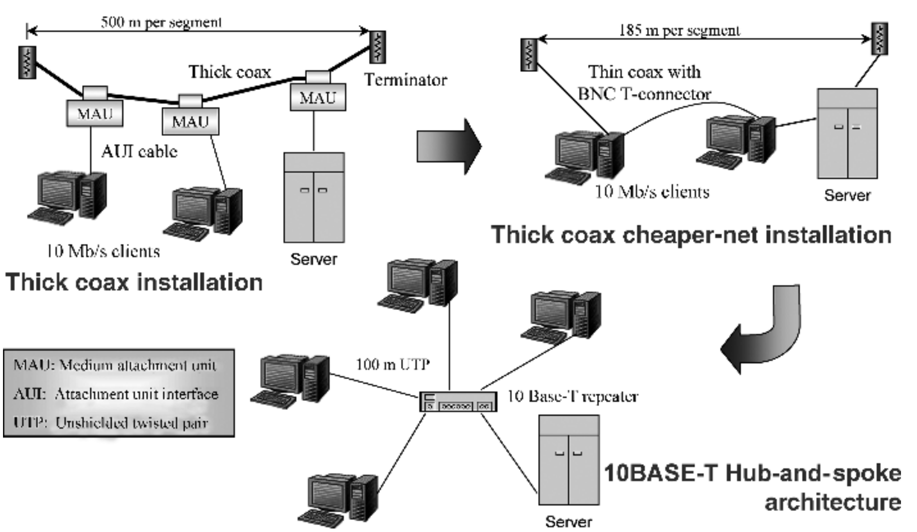

FIGURE 1.9 Evolution of Ethernet topologies.

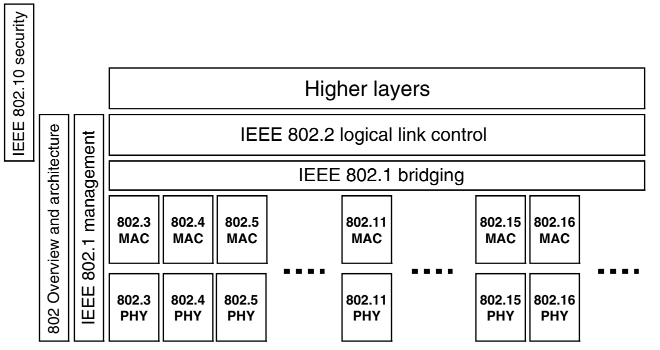

FIGURE 1.10 Organization of IEEE 802 standard series.

published this standard directly. In the mid 1990s, 100 Mb/s fast Ethernet was developed under IEEE 802.3 and 100VG-AnyLAN under IEEE 802.12. In the late 1990s, IEEE 802.3 approved the gigabit Ethernet and more recently 10 Gb/s Ethernet was introduced, mostly for backbone networking in metropolitan areas. Currently, 100 Gb/s Ethernet [Cvi08] is under development in the IEEE 802.3 community. These advances have materialized based on design of new physical layers for more efficient transmission over a variety of wired media.

In general, the LAN industry has developed a number of standards, mostly under the IEEE 802 community. Figure 1.10 shows an overview of the important IEEE 802 community standards. The 802.1 and 801.2 parts are common for all the standards, 802.3, 802.4 and 802.5 are wired LANs, and 802.9 is the so called ISO-Ethernet that supports voice and data over the traditional Ethernet mediums. IEEE 802.6 corresponds to metropolitan area networking and IEEE 802.11, 15, and 16 are related to WLAN, WPAN, and WMAN. IEEE 802.14 is devoted to cable-modem-based networks providing Internet access through cable TV distribution networks operating over coaxial cable wiring and fiber originally installed for TV distribution. IEEE 802.10 is concerned with security issues and operates at higher layers of the protocols. Newer standards beyond IEEE 802.16 are being developed, but these are not shown in Figure 1.10.

1.3.3 Evolution of the IEEE 802.11 Wireless Local-Area Network

Gfeller, at the IBM Rüschlikon Laboratories in Switzerland, first introduced the idea of a WLAN in late 1970s [Gfe80] as a method for local area networking in manufacturing areas. Diffuse infrared (IR) technology was selected for the implementation to avoid interference with electromagnetic signals radiating from machinery and to avoid dealing with long-lasting administrative procedures with frequency administration agencies. Ferrert at HP's Pal Alto Research Laboratories in California performed the second project on WLANs around the same time [Fer80]. In this project, a 100 kb/s direct sequence spread spectrum (DSSS) WLAN operating at around 900 MHz was developed for office areas.

WLANs need a bandwidth of at least several tens of megahertz, but they did not have a market compatible in strength with the cellular voice industry that originally started with two pieces of 25 MHz bands that produced a huge market. The dilemma for the frequency administration agencies was to justify a large frequency allocation for a product with a weak market. In the mid 1980s, the FCC found two solutions for this problem. The first and the simplest solution was to avoid the 1–2 GHz bands used for the cellular telephone and PCS applications and approve higher frequencies at several tens of gigahertz where plenty of unused bands were available. This solution was first negotiated between Motorola and the FCC and resulted in Motorola's Altair, the first WLAN product operating in licensed 18–19 GHz bands. Motorola had actually established a headquarters to facilitate user negotiation with the FCC for the usage of WLANs in different areas. A user who changed the location of operation of their WLAN substantially (from one town to another) contacted Motorola and they would manage the necessary frequency administration issues with the FCC.

The second and more innovative approach was resorting to unlicensed frequency bands as the solution. In response to the applications for bands for WLAN projects mentioned in the previous section and motivated by studies for various implementations of WLANs [Pah85], Mike Marcus of the FCC initiated the release of the unlicensed ISM bands in the May of 1985 [Mar85]. The ISM bands were the first unlicensed bands for consumer product development and played a major role in the development of the WLAN and later on the WPAN industry. Encouraged by the FCC ruling [Mar85] and some visionary publications in wireless office information networks summarizing previous works and addressing the future directions in this field [Pah85,Pah88, Kav87], a number of WLAN product development projects mushroomed almost exclusively over the North American continent. By the late 1980s the first generation of WLAN products using three different technologies, licensed bands at 18–19 GHz, spread spectrum in the ISM bands around 900 MHz, and IR appeared in the market. At around the same time, a standardization activity for WLANs under IEEE 802.4L was initiated that was soon converted into an independent group – IEEE 802.11 that was finalized in 1997.

Another WLAN standardization activity that started in 1992 was the high-performance radio LAN (HIPERLAN). This ETSI-based standard aimed at high performance LANs with data rates of up to 23 Mb/s that was an order of magnitude higher than the original 802.11 data rates of 2 Mb/s. To support these data rates, the HIPERLAN community was able to secure two unlicensed 200 MHz bands: 5.15–5.35 GHz and 17.1–17.3 GHz for WLAN operation. This encouraged the FCC to release the so-called Unlicensed National Information Infrastructure (U-NII) bands in 1997 when the original HIPERLAN standard (now called HIPERLAN/1) was completed. The U-NII bands were used by IEEE 802.11a and HIPERLAN/2 projects for the implementation of 54 Mb/s orthogonal frequency division multiplexing (OFDM)-based WLANs which was completed in 1999.

In the first half of the 1990s, WLAN products were expecting a sizable market of around a few billion dollars per year for shoebox-sized products used for LAN extension in indoor areas and this did not materialize. Under this situation, two new directions for product development emerged. The first and simplest approach was to take the existing shoebox-type WLANs, boost up their transmitted power to the maximum allowed under regulations, and equip them with directional antennas for outdoor interbuilding LAN interconnects. These technically simple solutions would allow coverage of up to a few tens of kilometers with suitable rooftop antennas. The new inter-LAN wireless bridges could connect corporate LANs that were within range. The cost of the inter-LAN wireless solution was much cheaper than the wired alternative, T1-carrier lines, leased from the PSTN service providers. This technology later evolved into point-to-multipoint WiMAX metropolitan area networks to solve the "last mile" problem for Internet service providers, which is discussed later. The second alternative was to reduce the size and cost of the design to a Personal Computer Memory Card International Association (PCMCIA) WLAN card to be

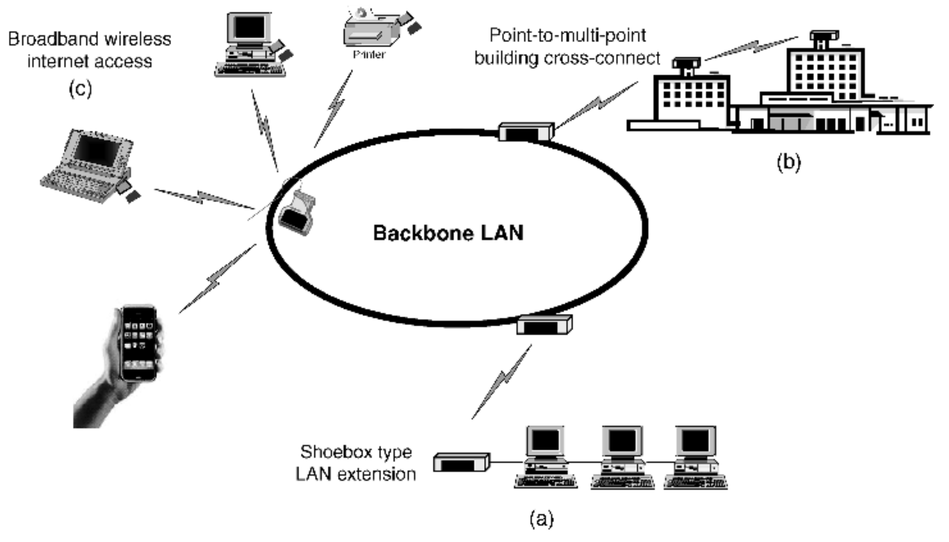

FIGURE 1.11 Evolution of WLAN products and applications: (a) legacy LAN-extension; (b) inter-LAN bridge; (c) broadband wireless Internet access.

used with laptops that were enjoying a sizable growth and demanded mobility for LAN connectivity. These products opened a new horizon for massive market development for WLANs in small office and home office (SOHO) networking and hot-spot Internet access which resulted in an exponential growth of the WLAN industry in the past decade. Most recently, WLANs are being integrated in most mobile phones and smartphones. To complement the home and office networking products, there are also low-cost products for LAN extension that can convert a serial port or Ethernet connector to a WLAN interface for desktop PC or printer connections. Figure 1.11 illustrates the evolution of applications for the WLANs.

Figure 1.12 illustrates the chronology of the evolution of the WLAN industry. The first small hump after the emergence of the technology was halted by the lack of frequency bands. The second and larger hump evolved after the release of unlicensed ISM bands which resulted in the shoebox products for LAN extension in the early 1990s. The third period of continual growth started after completion of the first IEEE 802.11 standard at 2 Mb/s followed by release of IEEE 802.11b at 11 Mb/s and IEEE 802.11a/g and "n" to support 54 Mb/s and over 100 Mb/s consecutively. These technologies supported successful expansion of the market to home networking, hotspots, corporate networking, and home access. More recently, WLAN signals are being exploited for localization applications as a softer product complementing global positioning system (GPS) technology which does not work properly in indoor and urban areas.

1.3.4 Internet Access to Home and IEEE 802.16

The connection between a network provider and the customer which provides the access to the network is very important for network providers. In the PSTN and cable TV industries this connection is referred to as the "last mile". The last mile connection is important because it is the route to get any information deliverable to the customer for generating

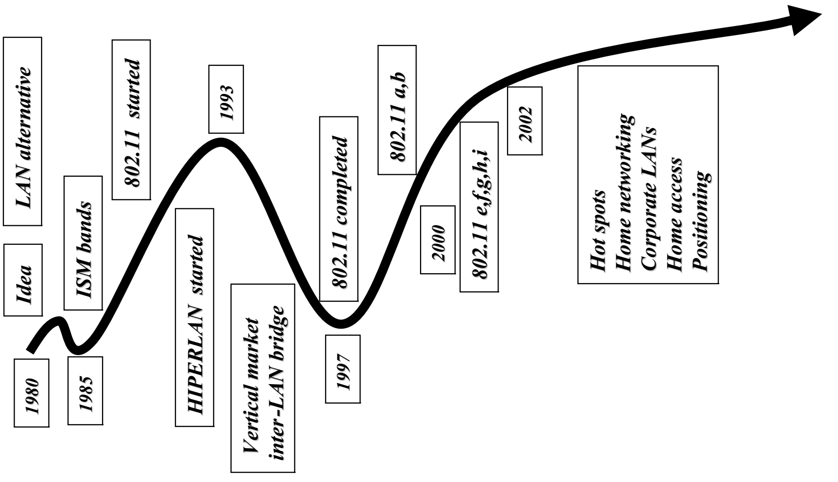

FIGURE 1.12 Chronology of the evolution of the WLAN industry.

income. However, it is an expensive challenge, because laying wires or cables is a considerably laborious undertaking. For that reason, a wireless solution to the last-mile problem has always attracted attention. The traditional PSTN service has been the analog POTS over the twisted-pair wirings and the cable TV distributors were using multichannel analog TV over coaxial cable. In modern times, the need for broadband Internet access has stimulated a number of innovative approaches in this industry. In office environments, the cost of the installation of the access leg of the network can be better justified by a larger size of the income from customer service. In the home environment, where usually income is generated from only one private user, the justification of the cost of making the connection becomes more challenging. In addition, the diversity of terminals used in the home environment is very wide. Most of the evolving terminals shown in Figure 1.2 are used at home. Figure 1.13 provides a classification of the home equipment demanding networking. Different classes need different technologies to connect to one another and they use different home access techniques to connect to WANs. We discuss local networking of this equipment in the next subsection, and in the rest of this section we focus on the access technologies.

Figure 1.14 illustrates the traditional networking connections in most residences. A typical traditional residence in the USA is connected to the PSTN for telephone services, the Internet for web access, and a cable network for multichannel TV services. Within the home, computers and printers are connected to the Internet through voice-band modems, DSL services, or cable modems. The telephone services and security systems are connected through PSTN wiring. The TV is connected to multichannel services through HFC cables or satellite dishes. Audio and video entertainment equipment, such as video cameras and stereo systems, and other computing systems, such as laptops, are either isolated or have proprietary wired connections. This fragmented networking environment has prompted a number of recent initiatives to create a unified home network. The home networking industry started in the early 2000s by the design of the so-called home or residential gateways to connect the increasing number of information appliances at home through a single Internet connection.

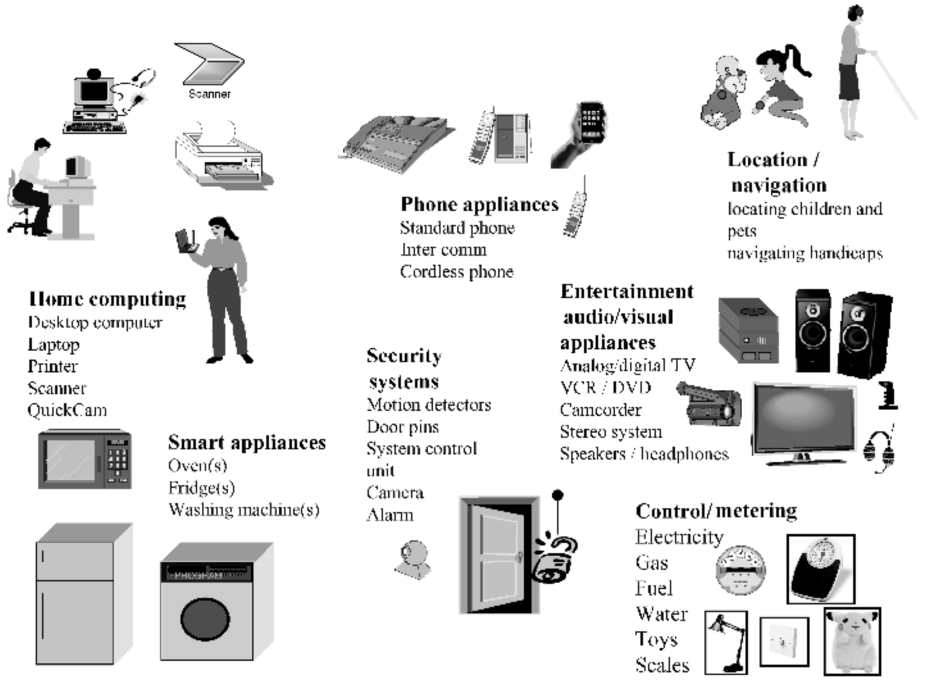

FIGURE 1.13 Classification of home equipment demanding networked operation.

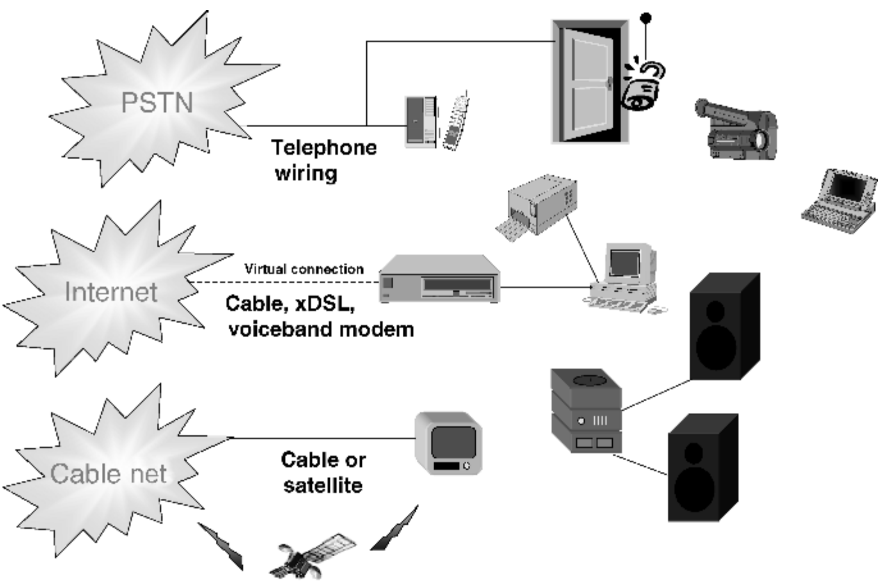

FIGURE 1.14 Traditional fragmented home access and distribution networks.

The early home access technology was based on voice-band modems. Today, broadband home access (with data rates on the order of 10 Mb/s) is provided through cable modems and DSL services over the telephone lines. Cable modems operate on the cable TV wiring. Some of the TV channel frequency bands are allocated to cable modems to provide broadband access to the Internet. The cable distribution in the residential areas has a bus topology that is optimally designed for one-way TV signal distribution. The bus carries all the stations in the neighborhood and the cable-TV box selects the station for the TV and if it is a scrambled paid channel it also de-scrambles the signal. To control the set-top boxes, a reverse channel is available in all modern cable wiring. Broadband cable services use one of the video channels and the reverse channel to establish a two-way communication and access to Internet. The DSL services use the 25 kHz–1.1 MHz bands on the telephone wirings to support broadband Internet access to the users. The topology of the telephone line is a star topology that connects every user directly to the end office where the DSL data is directed to the Internet through a router. The latest services for selected areas in the USA are the fiber to home solutions which are more popular in some other countries, such as South Korea or Japan.

Fiber is an excellent medium with respect to information capacity but is not readily available to most end users worldwide. Fiber optic lines are generally laid underground in conduits requiring a relatively expensive installation which poses an economical challenge for their rapid deployments worldwide.

For places with wiring problems, a wireless solution to the last mile problem has attracted considerable attention in the past decade. These services are sometimes referred to as fixed-wireless services. The advantage of using fixed-wireless solutions is that it does not involve wiring the streets. If there is no available wiring in the neighborhood, then a wireless solution is certainly the main economical solution, and for that reason it has become very popular in countries where networking infrastructure is limited. WLAN technologies can be used for this purpose, as we discussed earlier, by changing the antenna and boosting the transmitting power they can cover up to a few miles. Without changing the power, if the antennas are posted in heights outside, WLANs should easily cover a mile in line-of-sight (LOS) conditions as an inter-LAN bridge. Another alternative for broadband wireless home access is to use the IEEE 802.16 technologies. IEEE 802.16 has been working on this solution since the late 1990s. Other wireless alternatives are direct satellite TV broadcasting and 3G wireless networks. Direct broadcast suffers from the lack of a reverse channel and high delay that challenges the implementation of broadband services on this medium. The high-speed 3G wireless packet data services are expected to provide up to 2 Mb/s that is very suitable for Internet access. The data rates on these systems are lower and they are using licensed bands that ultimately may be expensive. Figure 1.15 summarizes the existing solutions for the home access technologies.

The most popular of all wireless solutions in recent years has been the IEEE 802.16 solution. This standard committee officially started in 1999 for the so-called local multipoint distribution system (LMDS). But it was a short-term hype attracting attention from cellular network equipment manufacturers. In 2001, the WiMAX forum industrial group was formed to improve 802.16 as an alternative to the popular DSL and cable modem technologies. This initiative finally introduced the IEEE 802.16d in 2004 as a fixed wireless solution and IEEE 802.16e, also known as mobile WiMax, in 2005. In comparison with WLAN solutions, WiMAX defines a more complex architecture to support QoS and mobility using outdoor antennas. Compared with cellular networks, it has smaller coverage and uses OFDM technology rather than CDMA and it has options for operation in

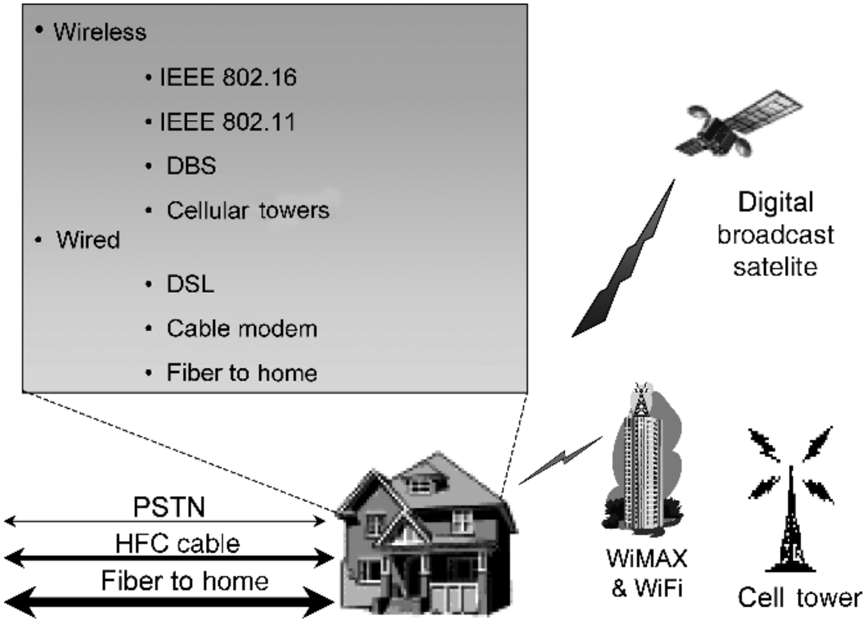

FIGURE 1.15 Broadband home access alternatives.

unlicensed as well as in licensed frequency bands. Therefore, WiMAX can be considered a technology between the WLAN and cellular networks with more similarities to WLANs. As a result, we discuss this technology as a part of Chapter 9.

1.3.5 Evolution of IEEE 802.15 Wireless Personal-Area Networks

Figure 1.16 illustrates the basic concept behind different classes of applications for local networks inside a home. The data rate, power consumption, and coverage for the networking technology that interconnects these devices are quite diversified, demanding different technologies. In response to that diversity of requirements, a number of local networking standards have evolved in the past decade. Figure 1.16 provides a simplified overview of the popular IEEE 802 standards on local networking as they relate to a variety of applications demanding data rates from a few kilobits per second up to a gigabit per second. For low data rate applications, such as utility metering, smart appliances, and security systems, the IEEE 802.15.4 and, for audio and short-range phones, IEEE 802.15.1 provide good solutions. For mid-range data rate applications for home computing and Internet access, IEEE 802.11 suits well, and IEEE 802.15.3 is a better choice for high-speed applications involving good quality video or large file transfers. We have already discussed IEEE 802.11WLANs in Section 1.3.3. Here, we give an overview of the IEEE 802.15 WPANs.

The very first personal area network (PAN) to be announced was the BodyLAN that emerged from a DARPA project in the mid 1990s. This was a low-power, small size, inexpensive, wireless PAN with modest bandwidth that could connect personal devices in many collocated systems with a range of around 5 feet [Den96]. Motivated by the BodyLAN

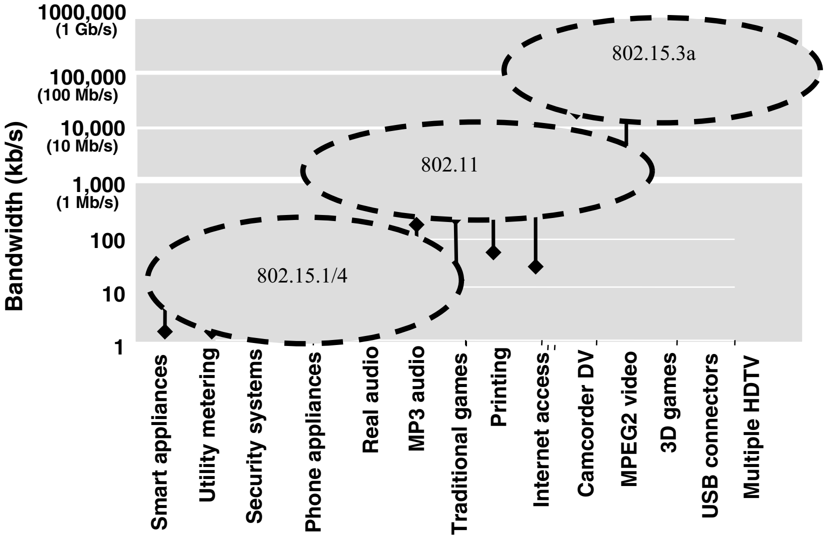

FIGURE 1.16 Applications bandwidth requirements and IEEE standards.

project, a WPAN group originally started in June 1997 as a part of the IEEE 802.11 standardization activity. In January 1998, the WPAN group published the original functionality requirement. In May 1998 the Bluetooth development was announced and a Bluetooth special group was formed within the WPAN group [Sie00]. In March 1999, IEEE 802.15 was approved as a separate group in the 802 community to handle WPAN standardization. This standardization committee adopted Bluetooth technology as its first standard, IEEE 802.15.1. Like legacy IEEE 802.11WLANs, the IEEE 802.15.1 Bluetooth technology operates in ISM unlicensed bands. Bluetooth operates at lower data rates than WLANs but uses a voice-oriented TDMA wireless access method that provides a better environment for supporting QoS needed for better quality of voice in an integrated voice and data service. The weakness of Bluetooth is its limitation on the number of simultaneous users and a slow network connection start up. IEEE 802.15.4 defined the first version of a low-power, low-cost, and low data rate WPAN in 2003. This standard is also known as ZigBee after the name of the industrial alliance group defining higher layer specifications for application development over MAC and PHY defined by IEEE 802.15.4. The MAC layer of the ZigBee is contention-based data-oriented CSMA with collision avoidance (CSMA/CA), which is a lighter version of the MAC used in IEEE 802.11 allowing larger numbers of users and faster network set up.

In 2003, a new wave of interest for ultra wideband (UWB) technology initiated the IEEE 802.15.3 group for standardization within 802.15. This group aimed at WPANs with extremely high data rates of up to 1 Gb/s to support short-range wireless connection for cable replacement and video-based applications. This group has defined two options for UWB WPANs in the unlicensed band in 3.4–10.6 GHz and for the time being has delayed their meetings until the market in this area evolves. Figure 1.17 shows a chronology of the evolution of the WPAN industry and the IEEE 802.15 standardization group.

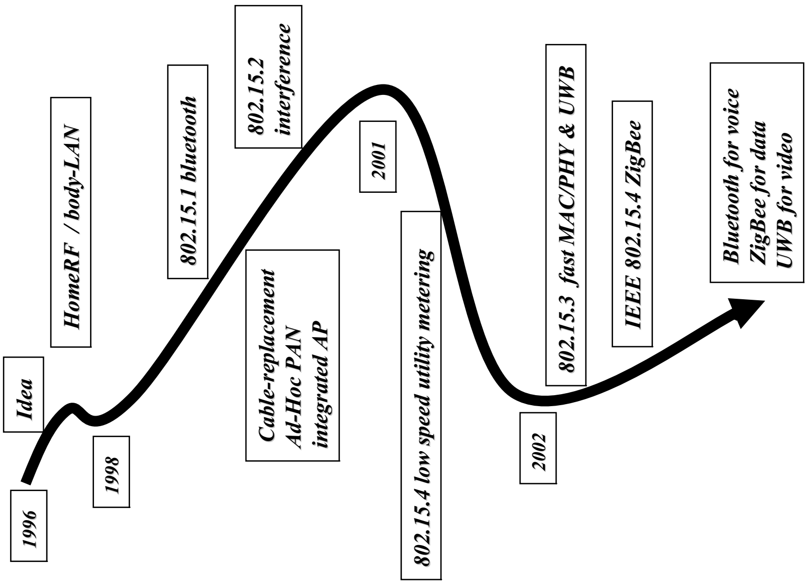

FIGURE 1.17 Chronology of evolution for WPAN industry.

1.4 STRUCTURE OF THE BOOK

This book is organized to start with a chapter providing an overview of information networks followed by four parts each including several chapters. The first chapter provides an overview of evolution of wired and wireless information networks from 1834 when the telegraph was introduced up to the modern time and the introduction of the iPhone and the Internet of Things.

Part One of the book is devoted to the fundamentals of transmission and access. This part of the book consists of four chapters describing the fundamentals of channel behavior, data transmission, coding, and MAC techniques. These chapters prepare students to understand the technical aspects related to emergence of new wired and wireless networking technologies. To the students with extensive background in signal analysis, these chapters provide a comprehensive summary of applied techniques that they may have seen in part in other courses. For students without a background in signal analysis these chapters provide an intuitive understanding of the lower layer issues, and with some extra effort they can learn the fundamentals of operation in these layers of networking. Chapter 2 is devoted to the characteristics of the wired and wireless medium. It provides the details of how the different guided and wireless media operate and how we can differentiate among cable, wire, fiber, and wireless networking in different frequencies. We discuss how bandwidth relates to length of a guided medium and how one can calculate coverage of a wireless network in different environments. Chapter 3 describes the fundamentals of data transmission techniques applied to wired and wireless networks. This chapter provides the details of how electrical signals are used as mathematical symbols to carry a bit stream generated by an application. Chapter 4 studies reliable transmission and coding techniques. Here, we provide a survey of coding techniques and the congestion control protocol applied to popular networking applications using simple examples explaining how we can implement them. Chapter 5 is devoted to MAC techniques used in a variety of LANs and wireless networks. This includes assigned access techniques such as FDMA, TDMA, and CDMA used in cellular telephone networks and different versions of CSMA techniques used in wired and wireless local networks connecting to the Internet.

Part Two of the book provides the details of technologies used in dominant WANs of the modern time, the Internet and cellular networks. Chapter 6 describes the interconnecting technologies used to implement the Internet. Chapter 6 describes issues related to addressing and QoS before a detailed description of bridging, switching, and routing technologies. These are issues and technologies used for the implementation of the Internet. Chapter 7 describes TDMA and CDMA cellular network technologies used in the GSM and 3G cellular networks and explains how these networks are deployed in the field. Here, we describe how packets are formed, how connections are made, and how the information transfers in connection based networks.

Part Three of the book is devoted to LANs and PANs. This part includes three chapters. Chapter 8 describes details of Ethernet. Here, we describe how an Ethernet packet is formed, how the medium is accessed by a packet, and how the bits in the packets are transmitted over different media. Chapter 9 describes the same feature for the IEEE 802.11 WLAN technologies known as WiFi and its extension to the WiMAX technology. Chapter 10 describes the different WPAN technologies used in lower speed Bluetooth and ZigBee technologies, as well as high-speed UWB systems. These chapters provide a wide variety of popular applications of the fundamental material presented in Part One of the book.

Part Four is the last part of the book, describing three important system aspects of networks: security, localization, and sensor networking. Chapter 11 is devoted to the security aspects of information networks. This chapter describes how the security of a network can be attacked and what can be done to protect a network and prevent these attacks. Chapter 12 addresses location sensing and geolocation systems. It describes how we can sense the radio-frequency (RF) signals in a way that it provides an indicator of the location and how we can use these indicators to localize a terminal in cellular or other wireless networks. Chapter 13 describes issues related to sensor networks and how we use WPAN technologies to implement them.

QUESTIONS

1. How is a wireless network different from a wired network? Explain at least five differences.
2. What is the difference between the 3G cellular networks, WLANs, and WPANs in terms of frequency of operation, orientation of the application over the network, and supported rates for data services?
3. Name the three major telecommunication services that dominate today's commercial services and give the approximate time when they were first introduced.
4. What is a WPAN? What is the difference between WPANs and WLANs? Name two example technologies for WPANs.
5. What is the difference between connectionless and connection-oriented backbone networks? Name the two major networks supporting these techniques.
6. What was the first transmission technique used for telecommunications? Was it voice or data? Analog or digital?

7. How many years did it take to go from the invention of the telegraph to transoceanic telegraph? How does it compare with the same thing for wireless telegraph? Explain why.
8. When and how were the first computer communication networks started?
9. How has the Internet evolved?
10. Name the three major existing infrastructures that support home networking.
11. What are the available access methods at homes?
12. What are the differences between a LAN and a WAN in terms of data rate, geographical coverage, and ownership?
13. What are the four generations of wired LANs?
14. What are the major home distribution technologies?
15. Name four home access technologies.
16. What is the difference between a MAN and a WAN?
17. Which standardization bodies regulate 3G cellular, WLAN, WPAN, and WiMax and what are the differences among these technologies in terms of frequency regulations, supporting data rates, and the coverage of the service?
18. What do you see as the next generation of the Internet and how does that relate to emergence of RFID applications?
19. Name three low speed (less than 1 Mbps), three medium speed (1–10 Mbps), and three high speed (10–1000 Mbps) applications. Give three IEEE standards which address the needs of these three classes of applications.
20. What is Ethernet and how does it relate to the IEEE 802 standardization activities? What was the speed of legacy Ethernet and what is the speed of the latest recommendations by the standardization committee?
21. What were the most popular TDMA and CDMA standards used in 2G cellular networks, where were these standards developed, and how did they evolve into the 3G networks?
22. What are the advantages of SONET over T1 transmission systems?
23. What are the differences between the different 802.15 standards in terms of applications that they target and the data rates they support?

PROJECT 1

Search Chapter 1 and the Internet (IEEE Explore, Wikipedia, Google Scholar, ACM Digital Library) to identify one area of research and one area in business development which you think are the most important for the future of the information networking industry. Give your reasoning as to why you think the area is important and cite at least one paper or a website to support your statement.