CHAPTER 1

BROADBAND ACCESS TECHNOLOGIES: AN OVERVIEW

In past decades we witnessed the rapid development of global communication infrastructure and the explosive growth of the Internet, accompanied by ever-increasing user bandwidth demands and emerging multimedia applications. These dramatic changes in technologies and market demands, combined with government deregulation and fierce competition among data, telcom, and CATV operators, have scrambled the conventional communication services and created new social and economic challenges and opportunities in the new millennium. To meet those challenges and competitions, current service providers are striving to build new multimedia networks. The most challenging part of current Internet development is the access network. As an integrated part of global communication infrastructure, broadband access networks connect millions of users to the Internet, providing various services, including integrated voice, data, and video. As bandwidth demands for multimedia applications increase continuously, users require broadband and flexible access with higher bandwidth and lower cost. A variety of broadband access technologies are emerging to meet those challenging demands. While broadband communication over power lines and satellites is being developed to catch the market share, DSL (digital subscriber line) and cable modem continue to evolve, allowing telecom and CATV companies to provide high-speed access over copper wires. In the meantime, FTTx and wireless networks have become a very promising access technologies. The convergence of optical and wireless technologies could be the best solution for broadband and mobile access service in the future. As new technology continues to be developed, the future access technology will be more flexible, faster, and cheaper. In this chapter

Broadband Optical Access Networks, First Edition. Leonid G. Kazovsky, Ning Cheng, Wei-Tao Shaw, David Gutierrez, and Shing-Wa Wong.

we discuss current access network scenarios and review current and emerging broad access technologies, including DSL, cable modem, optical, and wireless solutions.

1.1 COMMUNICATION NETWORKS

Since the development of telegraph and telephone networks in the nineteenth century, communication networks have come a long way and evolved into a global infrastructure. More than ever before, communications and information technologies pervade every aspect of our lives: our homes, our workplaces, our schools, and even our bodies. As part of the fundamental infrastructure of our global village, communication networks has enabled many other developments—social, economic, cultural, and political—and has changed significantly how people live, work, and interact.

Today's global communication network is an extremely complicated system and covers a very large geographic area, all over the world and even in outer space. Such a complicated system is built and managed within a hierarchical structure, consisting of local area, access area, metropolitan area, and wide area networks (as shown in Figure 1.1). All the network layers cooperate to achieve the ultimate task: anyone, anywhere, anytime, and any media communications.

Local Area Networks Local area networks (LANs) mainly connect computers and other electronic devices (servers, printers, etc.) within an office, a single building, or a few adjacent buildings. Therefore, the geographical coverage of LANs is very small, spanning from a few meters to a few hundred meters. LANs are generally not a part of public networks but are owned and operated by private organizations. Common

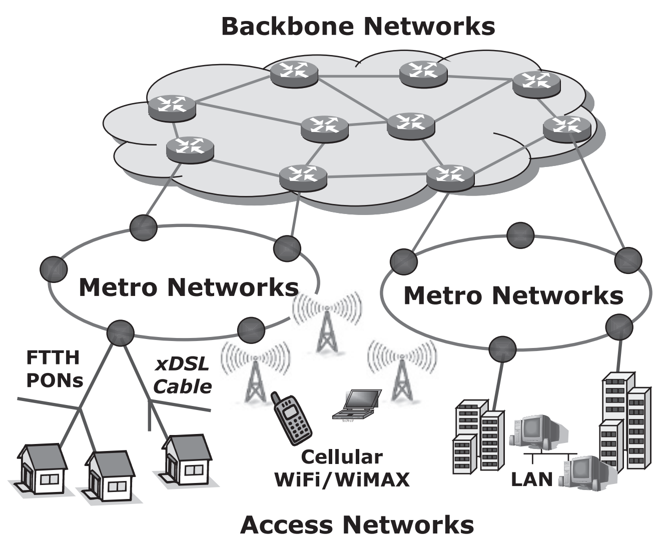

FIGURE 1.1 Hierarchical architecture of global communication infrastructure.

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topologies for LANs are bus, ring, star, or tree. The most popular LANs are parts of the Ethernet, supporting a few hundred users with typical bit rates of 10 or 100 Mb/s.

Access Networks The computers and other communication equipment of a private organization are usually connected to a public telecommunication networks through access networks. Access networks bridge end users to service providers through twist pairs (phone line), coaxial cables, or other leased lines (such as OC3 through optical fiber). The typical distance covered by an access network is a few kilometers up to 20 km. For personal users, access networks use DSL or cable modem technology with a transmission rate of a few megabits per second; for business users, networks employ point-to-point fiber links with hundreds of megabits or gigabits per second.

Metropolitan Area Networks Metropolitan area networks (MANs) aggregate the traffic from access networks and transport the data at a higher speed. A typical area covered by a MAN spans a metropolitan area or a small region in the countryside. Its topology is usually a fiber ring connecting multiple central offices, where the transmission data rate is typically 2.5 or 10 Gb/s.

Wide Area Networks Wide area networks (WANs) carry a large amount of traffic among cities, countries, and continents. MAN multiplexes traffic from LANs and transports the aggregated traffic at a much higher data rate, typically tens of gigabits per second or higher using wavelength-division multiplexing (WDM) technology over optical fibers. Whereas a WAN covers the area of a nation or, in some cases, multiple nations, a link or path through a MAN could be as long as a few thousand kilometers. Beyond MANs, submarine links connect continents. Generally, the submarine systems are point-to-point links with a large capacity and an extremely long path, from a few thousand up to 10,000 km. Because these links are designed for ultralong distances and operate under the sea, the design requirements are much more stringent than those of their terrestrial counterparts. Presently, submarine links are deployed across the Pacific and Atlantic oceans. Some shorter submarine links are also widely used in the Mediterranean, Asian Pacific, and African areas.

Service Convergence Historically, communication networks provide mainly three types of service: voice, data, and video (triple play). Voice conversation using plain old telephony is a continuous 3.4-kHz analog signal carried by two-way, point-to-point circuits with a very stringent delay requirement. The standard TV signal is a continuous 6-MHz analog signal usually distributed with point-to-multipoint broadcasting. Data transmission is typically bursty with varying bandwidth and delay requirements. Because the traffic characteristics of voice, data, and video and their corresponding requirements as to quality of service (QoS) are fundamentally different, three major types of networks were developed specifically to render these services in a cost-effective manner: PSTN (public-switched telephone networks) for voice conversation, HFC (hybrid fiber coax) networks for video distribution, and the Internet for data transfer. Although HFC networks are optimized for video broadcasting, the inherent one-way communication is not suitable for bidirectional data or voice. PSTN adopts circuit switching technology to carry information with specific bandwidth or data rates, such as voice signals. However, circuit-switched networks are not very efficient for carrying bursty data traffic. With packet switching, the Internet can support bursty data transmission, but it is very difficult to meet stringent delay requirements for certain applications. Therefore, no single network can satisfy all the service requirements.

Emerging multimedia applications such as video on demand, e-learning, and interactive gaming require simultaneous transmission of voice, data, and video. Driven by user demands and stiff competition, service providers are moving toward a converged network for multimedia applications, which will utilize Internet protocol (IP) technologies to provide triple-play services. As VoIP (voice over IP) has been developed in the past few years and more recently IP TV has become a mature technology, all network services will converge into an IP-based service platform. Furthermore, the integration of optical and wireless technologies will make quadruple play (voice, data, video, and mobility) a reality in the near future.

1.2 ACCESS TECHNOLOGIES

Emerging multimedia applications continuously fuel the explosive growth of the Internet and gradually pervade every area of our lives, from home to workplace. To provide multimedia service to every home and every user, access networks are built to connect end users to service providers. The link between service providers and end users is often called the *last mile* by service providers, or from an end user's perspective, the *first mile*. Ideally, access networks should be a converged platform capable of supporting a variety of applications and services. Through broadband access networks, integrated voice, data, and video service are provided to end users. However, the reality is that access networks are the weakest links in the current Internet infrastructure. While national information highways (WANs and MANs) have been developed in most parts of the globe, ramps and access routes to these information highways (i.e., the first/last mile) are mostly bike lanes or at best, unpaved roads, causing traffic congestion. Hence, pervasive broadband access should be a national imperative for future Internet development. In this section we review current access scenarios and discuss the last-mile bottleneck and its possible solutions.

1.2.1 Last-Mile Bottleneck

Due to advances in photonic technologies and worldwide deployment of optical fibers, during the last decade the telecommunication industry has experienced an extraordinary increase in transmission capacity in core transport networks. Commercial systems with 1-Tb/s transmission can easily be implemented in the field, and the state-of-the-art fiber optical transmission technology has reached 10 Tb/s in a single fiber. In the meanwhile, at the user end, the drastic improvement in the performance of personal computers and consumer electronic devices has made possible expanding demands of multimedia services, such as video on demand, video conferencing,

TABLE 1.1 Multimedia Applications and Their Bandwidth Requirements

Application	Bandwidth	Latency	Other Requirements
Voice over IP (VoIP)	64 kb/s	200 ms	Protection
Videoconferencing	2 Mb/s	200 ms	Protection
File sharing	3 Mb/s	1 s	
SDTV	4.5 Mb/s/ch	10 s	Multicasting
Interactive gaming	5 Mb/s	200 ms	
Telemedicine	8 Mb/s	50 ms	Protection
Real-time video	10 Mb/s	200 ms	Content distribution
Video on demand	10 Mb/s/ch	10 s	Low packet loss
HDTV	10 Mb/s/ch	10 s	Multicasting
Network-hosted software	25 Mb/s	200 ms	Security

e-learning, interactive games, VoIP, and others. Table 1.1 lists common end-user applications and their bandwidth requirements. As a result of the constantly increasing bandwidth demand, users may require more than 50 Mb/s in the near future. However, the current copper wire technologies bridging users and core networks have reached their fundamental bandwidth limits and become the *first-last-mile bottleneck*. Delays in Web page browsing, data access, and audio/video clip downloading have earned the Internet the nickname "World Wide Wait." How to alleviate this bottleneck has been a very challenging task for service providers.

1.2.2 Access Technologies Compared

For broadband access services, there is strong competition among several technologies: digital subscriber line, hybrid fiber coax, wireless, and FTTx (fiber to the x, x standing for home, curb, neighborhood, office, business, premise, user, etc.). For comparison, Table 1.2 lists the bandwidths (per user) and reaches of these competing technologies. Currently, dominant broadband access technologies are digital

TABLE 1.2 Comparison of Bandwidth and Reach for Popular Access Technologies

Service	Medium	Downstream (Mb/s)	Upstream (Mb/s)	Max Reach (km)
ADSL	Twisted pair	8	0.896	5.5
ADSL2	Twisted pair	15	3.8	5.5
VDSL1	Twisted pair	50	30	1.5
VDSL2	Twisted pair	100	30	0.5
HFC	Coax cable	40	9	25
BPON	Fiber	622	155	20
GPON	Fiber	2488	1244	20
EPON	Fiber	1000	1000	20
Wi-Fi	Free space	54	54	0.1
WiMAX	Free space	134	134	5

subscriber loop and coaxial cable. For conventional ADSL (asymmetric DSL) technology, the bandwidth available is a few Mb/s within the 5.5-km range. Newer VDSL (very high-speed DSL) can provide 50 Mb/s, but the maximum reach is limited to 1.5 km. On the other hand, coaxial cable has a much larger bandwidth than twist pairs, which can be as high as 1 Gb/s. However, due to the broadcast nature of CATV system, current cable modems can provide each user with an average bandwidth of a few Mb/s. While DSL and cable provide wired solutions for broadband access, Wi-Fi (wireless fidelity), and WiMAX (worldwide interoperability for microwave access) provide mobile access in a LAN or MAN network. Even though a nominal bandwidth of Wi-Fi and WiMAX can be relatively higher (54 Mb/s in 100 m for Wi-Fi and 28 Mb/s in 15 km for WiMAX), the reach of such wireless access is very limited and the actual bandwidth provided to users can be much lower, due to the interference in wireless channels. As a LAN technology, the primary use of Wi-Fi is in home and office networking. To reach the central office or service provider, multiple-hop wireless links with WiMAX have to be adopted. An alternative technology that is also under development is MBWA (mobile broadband wireless access, IEEE 802.20), which is very similar to WiMAX (IEEE 802.16e). Compared to the fixed access solutions, the advantages of the wireless technologies are easy deployment and ubiquitous or mobile access, and the disadvantages are unreliable bandwidth provisioning and/or limited access range.

The bandwidth and/or reach of the copper wire and wireless access technology is very limited due to the physical media constraints. To satisfy the future use demand (>30 Mb/s), there is a strategic urgency for service providers to deploy FTTx networks. Currently, for cost and deployment reasons, FTTx is competing with other access technologies. Long term, however, only optical fiber can provide the unlimited capacity and performance that will be required by future broadband services. FTTx has long been dubbed as a future-proof technology for the access networks. A number of optical access network architectures have been standardized (APON, BPON, EPON, and GPON), and cost-effective components and devices for FTTx have matured. We are currently witnessing a worldwide deployment of optical access networks and a steady increase in FTTx users.

1.3 DIGITAL SUBSCRIBER LINE

Digital subscriber line (also called *digital subscriber loop*) is a family of access technologies that utilize the telephone line (twisted pair) to provide broadband access service. While the audio signal (voice) carried by a telephony system is limited from 300 to 3400 Hz, the twisted pair connecting the users to the central office is capable of carrying frequencies well beyond the 3.4-kHz upper limit of the telephony system. Depending on the length and the quality of the twisted pair, the upper limit can extend to tens of megahertz. DSL takes advantage of this unused bandwidth and transmits data using multiple-frequency channels. Thus, some types of DSL allow simultaneous use of the telephone and broadband access on the same twisted pair.

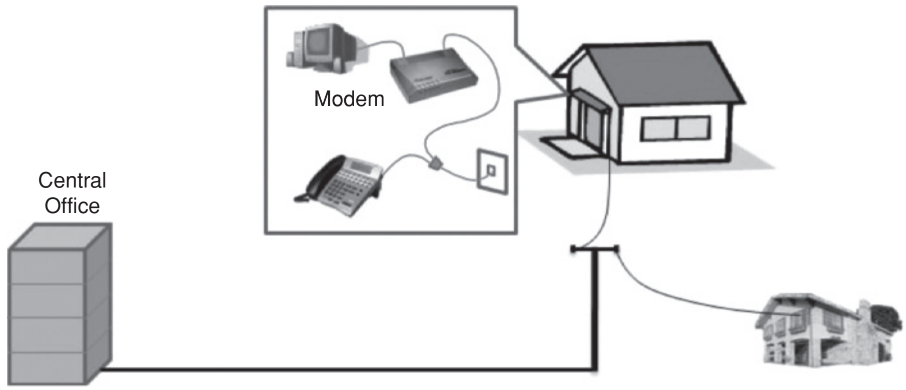

FIGURE 1.2 DSL access networks.

Figure 1.2 shows the typical setup of a DSL configuration. At the central office, a DSLAM (DSL access multiplexer) sends the data to users via downstream channels. At the user side, a DSL modem functions as a modulator/demodulator (i.e., receives data from DSLAM and modulates user data for upstream transmission).

1.3.1 DSL Standards

DSL comes in different flavors, supporting various downstream/upstream bit rates and access distances. DSL standards are defined in ANSI T1, and ITU-T Recommendation G.992/993. Table 1.2 lists various DSL standards and their performance. Collectively, these DSL technologies are referred to as *xDSL*. Two commonly deployed DSL standards are ADSL and VDSL.

As its name suggests, ADSL supports asymmetrical transmission. Since the typical ratio of traffic asymmetry is about 2 : 1 to 3 : 1, ADSL becomes a popular choice for broadband access. In addition, there is more crosstalk from other circuits at the DSLAM end. As the upload signal is weak at the noisy DSLAM end, it makes sense technically to have upstream transmission at a lower bit rate. Depending on the length and quality (such as the signal-to-noise ratio) of the twisted pair, the downstream bit rate can be as high as 10 times the upstream transmission. The maximum reach of ADSL is 5500 m. While ADSL1 can support a downstream bit rate up to 8 Mb/s and an upstream data rate up to 896 kb/s, ADSL2 supports up to 15 Mb/s downstream and 3.8 Mb/s upstream.

To support higher bit rates, the VDSL standard was developed after ADSL. Trading transmission distance for data rate, VDSL can support a much higher data rate but with very limited reach. VDSL1 standards specify data rates of 50 Mb/s for downstream and 30 Mb/s for upstream transmission. The maximum reach of VDSL1 is limited to 1500 m. The newer version of VDSL standards, VDSL2, is an enhancement of

VDSL1, supporting a data rate up to 100 Mb/s (with a transmission distance of 500 m). At 1 km, the bit rate will drop to 50 Mb/s. For reaches longer than 1.6 km, the VDSL2 performance is close to ADSL. Because of its higher data rates and ADSL-like long reach performance, VDSL2 is considered to be a very promising solution for upgrading existing ADSL infrastructure.

ADSL and VDSL are designed for residential subscribers with asymmetric bandwidth demands. For business users, symmetrical connections are generally required. Two symmetrical DSL standards, HDSL and SHDSL, are developed for business customers. While HDSL supports a T1 line data rate at 1.552 Mb/s (including 8 kb/s of overhead) with a reach of about 4000 m, SHDSL can provide a 6.696-Mb/s data rate with a maximum reach of 5500 m. However, HDSL and SHDSL do not support simultaneous telephone service, as most business customers do not have a requirement for a simultaneous voice circuit.

1.3.2 Modulation Methods

DSL uses a DMT (discrete multitone) modulation method. In DMT modulation, complex-to-real inverse discrete Fourier transform is used to partition the available bandwidth of the twisted pair into 256 orthogonal subchannels. DMT is adaptive to the quality of the twisted pair, so all the available bandwidth is fully utilized. The signal-to-noise ratio of each subchannel is monitored continuously. Based on the noise margin and bit error rate, a set of subchannels are selected, and a block of data bits are mapped into subchannels. In each subchannel, QAM (quadrature amplitude modulation) with a 4-kHz symbol rate is used to modulate the bit stream onto a subcarrier, leading to 60 kb/s per channel. Typically, the frequency range between 25 and 160 kHz is used for upstream transmission, and 140 kHz to 1.1 MHz is used for downstream transmission.

1.3.3 Voice over DSL

DSL was designed originally to carry data over phone lines, and DSL signal is separated from voice signal. Recently, new protocols have been proposed to merge voice and data at the circuit level. With advanced coding technologies, a 64-kb/s digitized voice signal can be compressed to 8 kb/s or less, thus allowing more voice channels to be carried over the same phone line. A voice over a DSL (VoDSL) gateway converts and compresses the analog voice signal to digital bit streams, so that calls made over VoDSL are indistinguishable from conventional calls. Usually, 12 to 20 voice channels can be carried over a single DSL line, depending on the transmission distance and the signal quality. A VoDSL system can be integrated into higher-layer protocols such as IP and ATM. Early DSL networks used ATM to ensure QoS, where ATM virtual circuits were used for the voice traffic. ADSL and VDSL networks migrate to packet-based transport, and they use packet-switched based virtual circuits instead of ATM ones.

1.4 HYBRID FIBER COAX

Cable networks were originally developed for a very simple reason: TV signal distribution. Therefore, cable networks are optimized for one-way, point-to-multipoint broadcasting of analog TV signals. As optical communication systems were developed, most cable TV systems have gradually been upgraded to hybrid fiber coax (HFC) networks, eliminating numerous electronic amplifiers along the trunk line. However, before cable access technology can be deployed, a return pass must be implemented for upstream traffic. To support two-way communication, bidirectional amplifiers have to be used in HFC systems, where filters are deployed to split the upstream (forward) and downstream (reverse) signals for separate amplification.

Figure 1.3 presents the network architecture of a typical HFC network. In HFC networks, analog TV signals are carried from the cable headend to distribution nodes using optical fibers, and from the distribution node, coaxial cable drops are deployed to serve 500 to 2000 subscribers. As shown in the figure, an HFC network is a shared medium system with a tree topology. In such a topology, multiple users share the same HFC infrastructure, so medium access control is required in upstream transmission while downstream transmission uses a broadcast scheme. A cable modem deployed at the subscriber end provides data connection to the cable network, while at the headend, the cable modem termination system connects to a variety of data servers and provides service to subscribers.

Compared with the twisted pairs in a telephone system, coaxial cables have a much higher bandwidth (1000 MHz), thus can support a much higher data rate. Depending on the signal-to-noise ratio on the coaxial cable, 40 Mb/s can be delivered to the end users with QAM modulation. For upstream transmission, QPSK can deliver up to a 10-Mb/s data rate. However, as cable systems are shared-medium networks, the bandwidth is thus shared by all the cable modems connected to the network. By contrast, DSL uses dedicated twist pairs for each user, thus no bandwidth sharing for different users. Furthermore, as the transmission bandwidth must be shared by multiple users, medium access control protocol must be deployed to govern upstream transmission. If congestion occurs in a specific channel, the headend must be able to instruct cable modems to tune its receiver to a different channel.

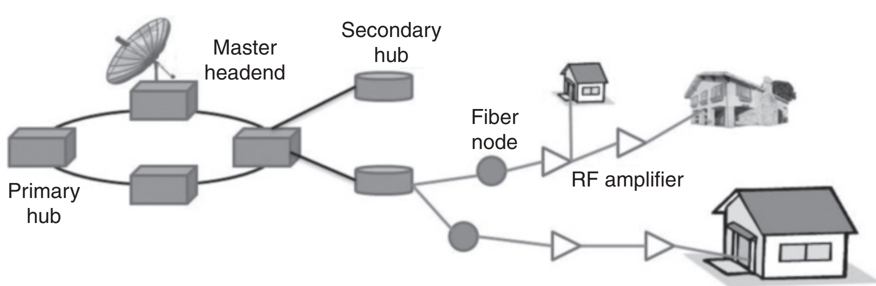

FIGURE 1.3 HFC access networks.

1.4.1 Cable Modem

Cable modems were developed to transport high-speed data to and from end users in an HFC network. Traditional TV broadcasting occupies frequencies up to 1 GHz, with each TV channel occupying 6 MHz of bandwidth (Part 76 in the FCC rules). A cable modem uses two of those 6-MHz channels for data transmission. For upstream transmission, a cable modem sends user data to the headend using a 6-MHz band between 5 and 42 MHz. At the same time, the cable modem must tune its receiver to a 6-MHz band within a 450- to 750-MHz band to receive downstream data. While a QAM modulation scheme is used for downstream data, a QPSK modulation scheme is usually selected for upstream transmission, as it is more immune to the interference resulting from radio broadcasting.

1.4.2 DOCSIS

DOCSIS (Data Over Cable Service Interface Specifications), developed by CableLabs, a consortium of equipment manufactuers, is the current standard for cable access technology. DOCSIS defines the functionalities and properties of cable modems at a subscriber's premises and cable modem termination systems at the headend. As its name suggests, DOCSIS specifies the physical layer characteristics, such as transmission frequency, bit rate, modulation format, and power levels, of cable modem and cable modem termination systems, but also the data link layer protocol, such as frame structure, medium access control, and link security. Three different versions of DOCSIS (1.0/2.0/3.0) was developed during the past decade and were later ratified as ITU-T Recommendation J.112, J.122, and J.222. Although some compromise is needed as cable networks are a shared medium, DOCSIS offers various classes of service with medium access control. Such QoS features in DOCSIS can support applications (such as VoIP) that have stringent delay or bandwidth requirements.

Physical Layer The upstream PMD layer supports two modulation formats: QPSK and 16-QAM, and the downstream PMD layers uses 64-QAM and 256-QAM. The nominal symbol rate is 0.16, 0.32, 0.64, 1.28, 2.56, or 5.12 Mbaud. Therefore, the maximum downstream data rate is about 40 Mb/s and the upstream data rate is about 20 Mb/s. To mitigate the effect of noise and other detrimental channel effects, Reed–Solomon encoding, transmitter equalizer, and variable interleaving schemes are commonly used.

Data Link Layer The DOCSIS data link layer specifies frame structure, MAC, and link security. The frame structure used in HFC networks is very similar to the Ethernet in both the upstream and downstream directions. For the downstream direction, data frames are embedded in 188-byte MPEG-2 (ITU-T H.222.0) packets with a 4-byte header followed by 184 bytes of payload. Downstream uses TDM transmission schemes, synchronous to all modems. In the upstream direction, TDMA or S-CDMA are defined for medium access control. An upstream packet includes physical layer overhead, a unique word, MAC overhead, packet payload, and FEC bytes. MAC layer specifications also include modem registration, ranging, bandwidth allocation, collision detection and contention resolution, error detection, and data recovery. An access security mechanism in DOCSIS defines a baseline privacy interface, security system interface, and removable security module interface, to ensure information security in HFC networks.

1.5 OPTICAL ACCESS NETWORKS

Due to their ultrahigh bandwidth and low attenuation, optical fibers have been widely deployed for wide area networks and metro area networks. To some extent, multimode fibers were also deployed in office buildings for local area networks. Even though optical fibers are ideal media for high-speed communication systems and networks, the deployment cost was considered prohibitive in the access area, and copper wires still dominate in the current marketplace. However, as discussed in Section 1.2, emerging multimedia applications have created such large bandwidth demands that copper wire technologies have reached their bandwidth limits. Meanwhile, low-cost photonic components and passive optical network architecture have made fiber a very attractive solution. In the past few years, various PON architecture and technologies have been studied by the telecom industry, and a few PON standards have been approved by ITU-T and IEEE. FTTx becomes a mature technology in direct competition with copper wires. In fact, large-scale deployment has started in Asia, North America, and Europe, and millions of subscribers are enjoying the benefit of PON technologies.

1.5.1 Passive Optical Networks

Figure 1.4 illustrates the architecture of a passive optical network. As the name implies, there is no active component between the central office and the user premises. Active devices exist only in the central office and at user premises. From the central office, a standard single-mode optical fiber (feeder fiber) runs to a 1 : N passive optical power splitter near the user premises. The output ports of the passive splitter connects to the subscribers through individual single-mode fibers (distribution fibers). The transmission distance in a passive optical networks is limited to 20 km, as specified in current standards. The fibers and passive components between the central office and users premises are commonly called an optical distribution network. The number of users supported by a PON can be anywhere from 2 to 128, depending on the the power budget, but typically, 16, 32, or 64. At the central office, an optical line terminal (OLT) transmits downstream data using 1490-nm wavelength, and the broadcasting video is sent through 1550-nm wavelength. Downstream uses a broadcast and select scheme; that is, the downstream data and video are broadcast to each user with MAC addresses, and the user selects the data packet–based MAC addresses. At the user end, an optical network unit (ONU), also called an optical network terminal (ONT), transmits upstream data at 1310-nm wavelength. To avoid collision, upstream transmission uses a multiple access protocol (i.e., time-division multiple access) to assign time slots to

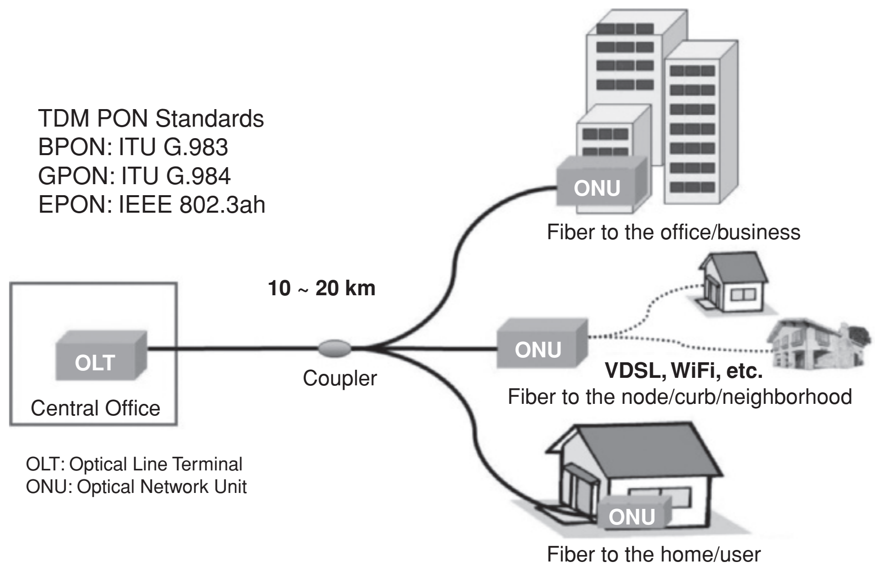

FIGURE 1.4 Passive optical networks.

each user. This type of passive optical network is called TDM PON. The ONU could be located in a home, office, a curbside cabinet, or elsewhere. Thus comes the so-called fiber-to-the-home/office/business/neighborhood/curb/user/premises/node, all of which are commonly referred to as *fiber to the x*. In the case of fiber-to-the-neighborhood/curb/node, twisted pairs are typically deployed to connect end users to the ONUs, thus providing a hybrid fiber/DSL access solution.

1.5.2 PON Standard Development

Early work of passive optical networks started in 1990s, when telecom service providers and system equipment vendors formed the FSAN (full service access networks) working group. The common goal of the FSAN group is to develop truly broadband fiber access networks. Because of the traffic management capabilities and robust QoS support of ATM (asynchronous transfer mode), the first PON standard, APON, is based on ATM and hence referred to as ATM PON. APON supports 622.08 Mb/s for downstream transmission and 155.52 Mb/s for upstream traffic. Downstream voice and data traffic is transmitted using 1490-nm wavelength, and downstream video is transmitted with 1550-nm wavelength. For upstream, user data are transmitted with 1310-nm wavelength. All the user traffic is encapsulated in standard ATM cells, which consists of 5-byte control header and 48-byte user data. APON standard was ratified by ITU-T in 1998 in Recommendation G.983.1. In the early days, APON was most deployed for business applications (e.g., fiber-to-the-office). However, APON networks are largely substituted with higher-bit-rate BPONs and GPONs.

Based on APON, ITU-T further developed BPON standard as specified in a series of recommendations in G.983. BPON is an enhancement of APON, where a higher data rate and detailed control protocols are specified. BPON supports a maximum downstream data rate at 1.2 Gb/s and a maximum upstream data rate at 622 Mb/s. ITU-T G.983 also specifies dynamic bandwidth allocation (DBA), management and control interfaces, and network protection. There has been large-scale deployment of BPON in support of fiber-to-the-premises applications.

The growing demand for higher bandwidth in the access networks stimulated further development of PON standards with higher capacity beyond those of APON and BPON. Starting in 2001, the FSAN group developed a new standard called gigabit PON, which becomes the ITU-T G.984 standard. The GPON physical media–dependent layer supports a maximum downstream/upstream data rate at 2.488 Gb/s, and the transmission convergence layer specifies a GPON frame format, media access control, operation and maintenance procedures, and an encryption method. Based on the ITU-T G.7041 generic framing procedure, GPON adopts GEM (a GPON encapsulation method) to support different layer 2 protocols, such as ATM and Ethernet. The novel GEM encapsulation method is backwardly compatible with APON and BPON and provides better efficiency than do Ethernet frames. Deployment of GPON had taken off in North America and largely replaced older BPONs and more.

While ITU-T rolled out BPON and GPON standards, IEEE Ethernet-in-the-first-mile working group developed a PON standard based on Ethernet. The EPON physical media–dependent layer can support maximum 1.25-Gb/s (effective data rate 1.0 Gb/s) downstream/upstream traffic. EPON encapsulate and transport user data in Ethernet frames. Thus, EPON is a natural extension of the local area networks in the user premises, and connects LANs to the Ethernet-based MAN/WAN infrastructure. Since there is no data fragment or assembly in EPON and its requirement on physical media–dependent layer is more relaxed, EPON equipment is less expensive than GPON. As Ethernet has been used widely in local area networks, EPON becomes a very attractive access technology. Currently, EPON networks have been deployed on a large scale in Japan, serving millions of users.

1.5.3 WDM PONs

As the user bandwidth demands keep increasing, current GPON or EPON will eventually no longer be able to satisfy the bandwidth requirement. There are a few possible solutions. One possibility is to split a single PON into multiple PONs so that each PON supports fewer users and each user gets more bandwidth. Another alternative is to use a higher bit rate, such as 10 Gb/s. In fact, an IEEE 802.3av study group is creating a draft standard on 10-Gb/s EPON. However, both solutions for higher bandwidth (i.e., higher bit rate or fewer users per PON) are not very cost-effective and do not scale very well as the bandwidth demands increase further. In addition, the power distribution of the passive splitter is fixed; that will lead to an uneven power budget for users and limit the transmission distance. Ultimately, WDM PON is the only future proof of technology that can satisfy any bandwidth demands.

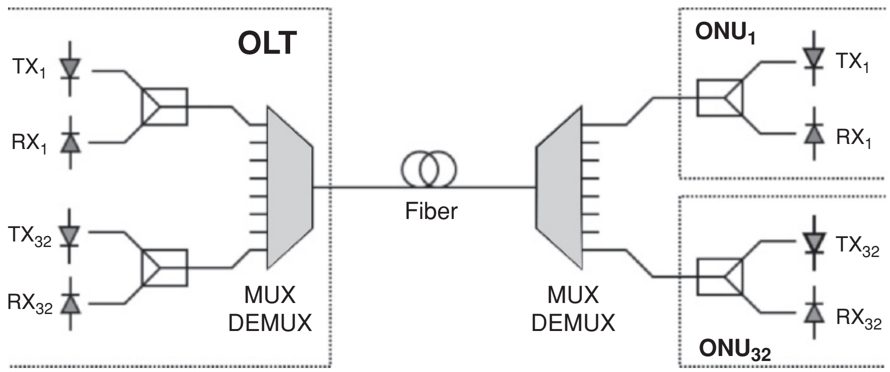

FIGURE 1.5 WDM passive optical networks.

Figure 1.5 shows the network architecture of WDM PONs. Transmitters with varying wavelengths will be deployed at the OLT and ONU sides, and a passive wavelength-division multiplexer will be inserted at the distribution node to separate and combine multiple wavelengths. Thus, the fiber distribution network will be kept passive. If the user bandwidth demands are not very large, or in the other words, a small number of users can still share a single wavelength, a passive power splitter following the WDM is used to broadcast the downstream traffic and combine the upstream traffic. In this case, multiple wavelengths separate a single PON into multiple logical TDM PONs. Each PON runs on a different wavelength, and fewer users share the bandwidth of a TDM PON. In addition, since the optical power is split for a smaller number of users, WDM PONs is less subject to optical power budget constraints, leading to long-reach access networks. If a user requires a large amount of bandwidth (e.g., a few gigabits per second), a single wavelength can be provided for this specific user; or in an extreme case, multiple wavelengths, hence a large bandwidth, can be provided to a single user if needed.

In WDM PONs, the equipment and resources at OLT are shared by fewer users, leading to higher cost per user. Hence, WDM PONs are considered much more expensive than TDM PONs. However, to support high-bandwidth applications, there will be a need in the near future to move from TDM access networks to WDM access networks. Currently, the way to migrate from current TDM access networks to WDM access networks in a cost-effective, flexible, and scalable manner is not at all clear. A method to upgrade the access service smoothly and cost-effectively from a current TDM FTTx network to a future WDM FTTx network with a minimum influence on legacy users is the object of intense research. Various approaches to implementing WDM have been and are being explored, and field deployment has begun in Asia (South Korea, to be exact). A number of schemes to incorporate WDM technology into access networks have been studied and tested in experiments, and the WDM FTTx network architecture exhibits certain exceptional features in the WDM implementation in either downstream, upstream, or both directions. As optical technology becomes cheaper and easier to deploy and end users demand ever-increasing bandwidth, WDM PONs will eventually make the first/last-mile bottleneck history.

1.5.4 Other Types of Optical Access Networks

In addition to the passive optical networks, TDM and WDM PONs, that we have discussed, other types of optical access networks have been developed over the years, including Ethernet over fiber, DOCSIS PON, RF PON, and free-space optical networks. Ethernet over fiber is essentially point-to-point Ethernet built on fiber links. DOCSIS and RF PON is two flavors of PON developed for cable companies. Free-space optical networks is a wireless access solution utilizing optical communication technologies.

Ethernet over Fiber Ethernet over fiber is deployed primarily in point-to-point topology. Typically, dedicated fiber connects a subscriber to the central office, and each subscriber requires two dedicated transceivers (one at the user premises and the other at the central office). This approach requires a large number of fibers and optical transceivers and thus incurs a large cost associated with fiber and equipment. Since each fiber link can run on its full capacity, Ethernet over fiber, which requires gigabit bandwidth, is used primarily for business subscribers. Figure 1.6 shows an

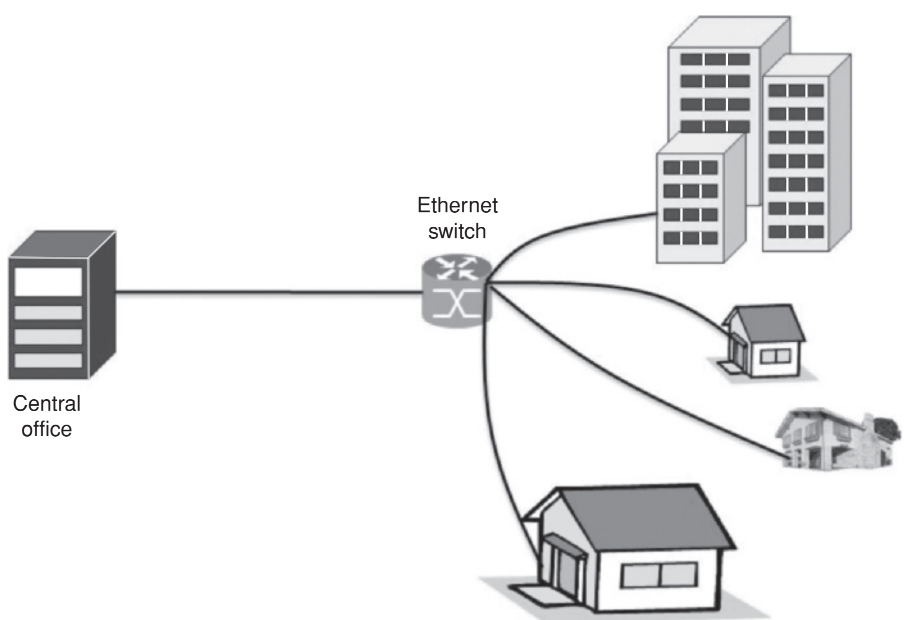

FIGURE 1.6 Point-to-point Ethernet optical access networks.

alternative architecture for Ethernet over fiber. A local Ethernet switch is deployed to the user sites. Individual fiber can then run from the switch to each user, and only a single fiber (bidirectional) or two fibers (unidirectional) connect the Ethernet switch to the central office. This approach reduces the number of fibers run from the central office but requires an active Ethernet switch in the field and requires at least two more transceivers than is the case on the left in the figure.

DOCSIS PON While telecom companies are deploying PONs worldwide on a large scale, MSOs (multisystem operators) need to upgrade their fiber coax systems to compete in FTTx markets. DOCSIS PON, or DPON, is developed to provide a DOCSIS service layer interface on top of PON architecture. DPON implements DOCSIS functionalities, including OAMP (operation, administration, maintenance, and provisioning) on existing PON systems, and thus allow MSOs to use set-top and DOCSIS equipment located in homes and headends over PONs. However, fundamentally, DPON service is based on current EPON or GPON MAC and physical layer standards. Therefore, DPON is just an application running on top of PON systems.

RF PON Radio-frequency PON (RF PON) is another flavor of passive optical networks developed for MSOs. RF PONs support RF video broadcasting signals over optical fibers. As MSOs expand the network footprint and launch new products using additional RF bandwidth, more active RF components are deployed and higher frequencies sometimes require RF electronics change-outs and respacing. As a consequence, HFC networks experience reduced signal quality, lower reliability, and higher operating and maintenance cost. RF PONs are a natural evolution of current HFC networks, as they offer backward compatibility with current RF video broadcasting technologies and provides significant cost reduction in network operation and maintenance.

OCDM PON Optical code-division multiplexing (OCDM) has been demonstrated recently as an alternative multiplexing technique for PONs. Similar to electronic CDMA technology, users in OCDM PONs are assigned orthogonal codes with which each user's data are encoded or decoded into or from optical pulse sequence. OCDM PONs can thus provide asynchronous communications and security against unauthorized users. However, the optical encoders and decoders for OCDM are expensive, and the number of users is limited by interference and noise.

Free-Space Optical Networks Unlike fiber optic communications, *free-space optical communication* (also called *optical wireless communication*) uses atmosphere as the communication medium. This is probably one of the old long-distance communication methods (e.g., smoke signals) used a few thousands years ago. During the past decades, there has been revived interest in free-space communication for satellite and urban environment. Particularly in the access networks, it can used to connect a subscriber directly to a central office. Figure 1.7 shows a typical setup

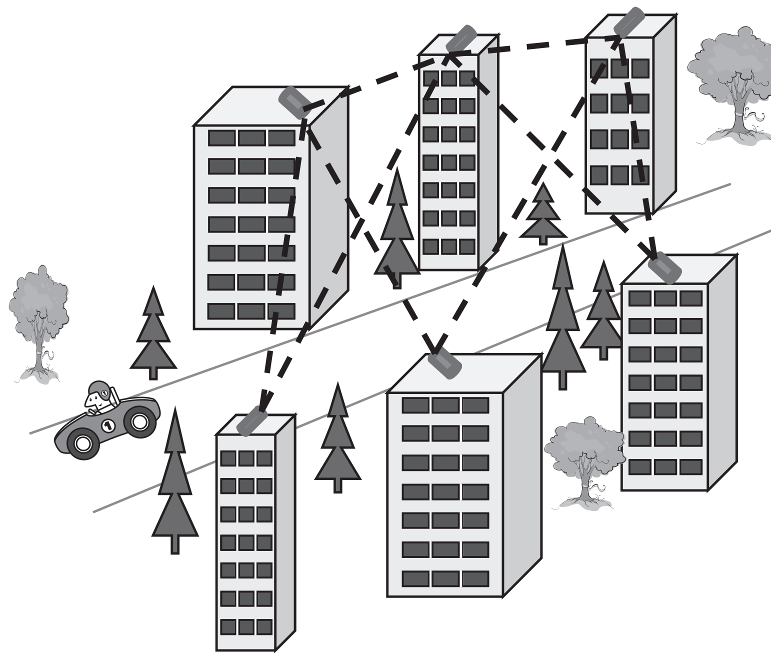

FIGURE 1.7 Free-space optical communications and networks. Point-to-point optical wireless links on the roofs of buildings form a mesh network for broadband access.

for urban free-space optical communication networks. Due to the line-of-sight requirement for free-space optical communications, optical transceivers are usually mounted on the tops of buildings, and telescopes are typically used in the transmitter to improve the alignment of optical links. Multiple point-to-point links can form a mesh network, improving its scalability and reliability. As a wireless technology, the cost of free-space optical communication is very low, about 10% of fiber optic communications, and the high-speed link can be set up and torn down in a couple hours. Compared to other wireless access technologies, it provides a higher data rate, longer reach, and better signal quality. So far, thousands of free-space optical links have been deployed. However, atmosphere is not an ideal transmission medium, due to attenuation and scattering at optical frequency. Turbulence, rain, and dense fog could be very challenging for free-space optical communication. For long-reach links, alignment of optical transmitters and receivers is also difficult, and an adaptive ray-tracking system might be needed for rapid pointing and accurate alignment. Potentially, survivable network topology, transmitter and receiver arrays, and adaptive and equalization technologies could help mitigate the atmospheric effect and alignment problem. Integration with wire line networks such as PONs can greatly improve the reliability and survivability of free-space optical access networks. In the future, we may witness more and more free-space optical networks in urban settings.

1.6 BROADBAND OVER POWER LINES

Ac power lines have long been considered a workable communication medium. For decades, utility companies have used power lines for signaling and control, but they are used primarily for internal management of power grids, household intercoms, and lighting controls. As deregulation of both the telecom and electricity industries was unfolding in the 1990s, broadband access over power lines became a possibility. As power lines reach more residences than does any other medium, significant efforts have been made to develop high-speed access over power lines. A number of solutions have been proposed and tested in the field. Even though DSL or cable currently dominates the broadband access services, and PONs are very promising for the near future, broadband over power lines (BPL) can still claim its part in the current market. For example, in some rural areas, building infrastructure to provide DSL or cable could be very expensive, while power-line communications could easily provide broadband services. Anywhere there is electricity there could be broadband over power lines. In addition, there is a great potential to network all the appliances in a household through the power line, thus providing a smart home solution. However, at present power-line communication technology and its market potential remain to be developed further.

1.6.1 Power-Line Communications

Figure 1.8 shows the topology of the electrical power distribution grid. The three-phase power generated at a power plant enters a transmission substation, where the three-phase power generated by the power generators is converted to extremely high

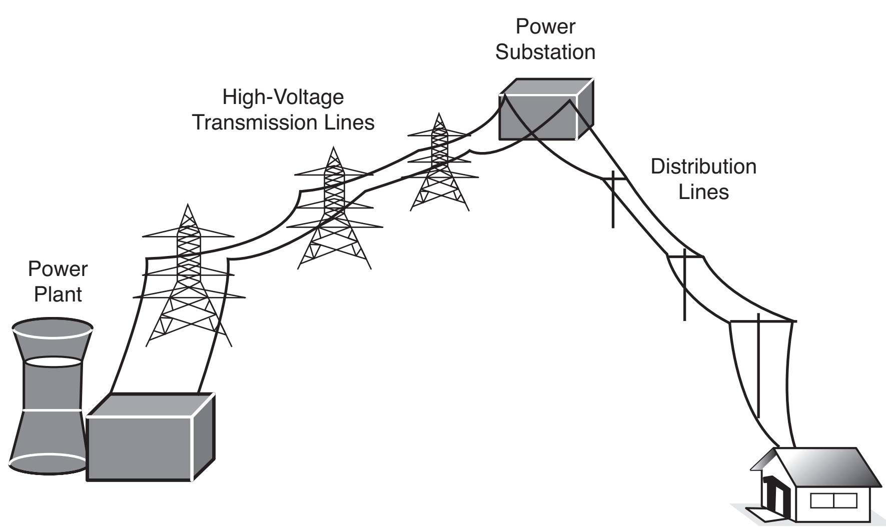

FIGURE 1.8 Electrical power transmission and distribution.

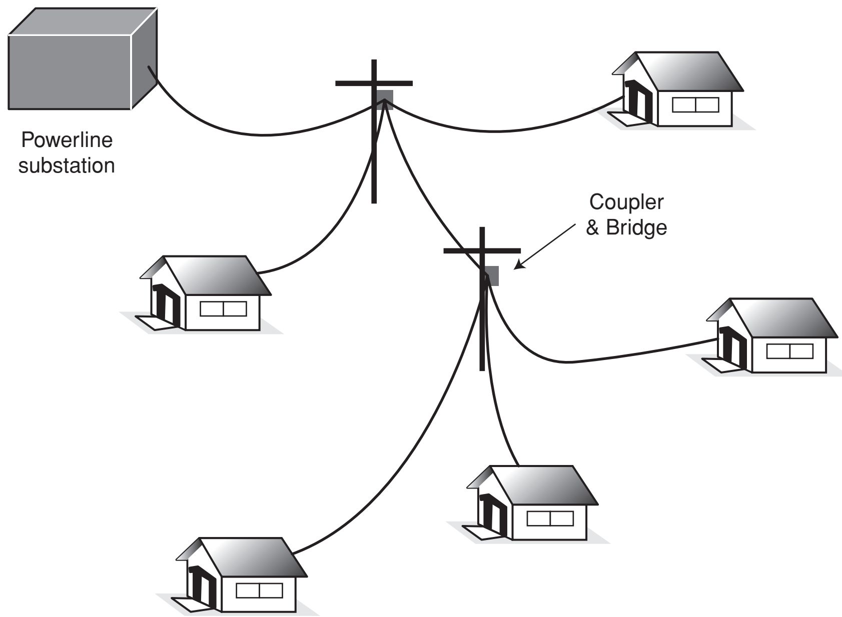

FIGURE 1.9 Broadband power-line communications.

voltages (155 to 765 kV) for long-distance transmission over the grid. Within the transmission grid, many power substations convert the extremely high transmission voltage down to distribution voltages (less than 10 kV), and this medium-voltage electricity is sent through a bus that can split the power in multiple directions. Along the distribution bus, there are regulator banks that regulate the voltage on the line to avoid overshoot or undershoot, and taps that send electricity down the street. At each building or house, there is a transformer drum attached to the electricity pole, reducing the medium voltage (typically, 7.2 kV) to household voltage (110 or 240 V).

Broadband over power lines utilizes the medium-voltage power lines to transmit data to and from each house, as shown in Figure 1.9. Typically, repeaters are installed along the power lines for long-distance data transmission, and some bypass devices allow RF signals to bypass transformers. In the last step of data transmission, the signals can be carried to each house by the power line or, alternatively, using Wi-Fi or other wireless technology for last-mile connection.

1.6.2 BPL Modem

A BPL modem plugs into a common power socket on the wall, sending and receiving data through a power line. On the other end, the BPL modem connects to computers or other network devices by means of Ethernet cables. In some cases, a wireless router can be integrated with a BPL modem. BPL modems transmit at medium to high frequencies, from a few megahertz to tens of megahertz. Typical

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data rates supported by a BPL modem range from hundreds of kilobits per second to a few megabits per second. Various modulation schemes can be used for power-line communications, including the older ASK (amplitude shift keying), FSK (frequency shift keying) modulation and newer DMT, DSSS (direct sequence spread spectrum) and OFDM (orthogonal frequency-division multiplexing) technologies. DMT, DSSS, or OFDM modulation is perferred in modern BPL modems, as it is more robust in handling interference and noise. Recent research has demonstrated a gigabit data rate over power lines using microwave frequencies via surface wave propagation. This technology can avoid the interference problems very common in power lines.

1.6.3 Challenges in BPL

BPL is a promising technology, but its development is relatively slow compared with DSL and cable. There are a number of technical challenges that must be overcome. A power line is not a very good medium for data transmission: Various transformers used in the electric grid do not pass RF signals, the numerous sources of signal reflections (impedance mismatches and lack of proper impedance termination) on power lines hinder data transmission, and noise from numerous sources (such as power motors) contaminates the transmission spectrum. Since power lines consist of untwisted and unshielded wire, their long length makes them large antennas emitting RF signals and interfering with other radio communications. Furthermore, a power line is a shared medium limiting the bandwidth delivered to each user and raising security concerns for private communications. All these issues have to be fully addressed before large-scale deployment can be implemented. Fortunately, much progress has been made through intensive research during recent decades. BPL is poised to be a promising technology for entry into the current highly competitive market.

1.7 WIRELESS ACCESS TECHNOLOGIES

Starting with RF communication and broadcasting, wireless communication technologies have had an incredibly powerful effect on the entire world since the beginning of the twentieth century. Nowadays, AM/FM radio and TV broadcasting blanket every continent except Antarctica; wireless cellular networks provide voice communication to hundreds of millions of users; satellites provide video broadcasting and communication links worldwide; and Bluetooth and wireless LANs support mobile services to individuals. Wireless networks are everywhere. The popularity of wireless technologies is due primarily to their mobility, scalability, low cost, and ease of deployment. Wireless technologies will continue to play an important part in our daily lives, and fourth-generation wireless networks will be able to provide quadruple play through seamless integration of a variety of wireless networks, including wireless personal networks, wireless LANs, wireless access networks, cellular wide area networks, and satellite networks. In recent years, a number of wireless technologies have been developed as alternatives to traditional wired access service (DSL, cable, and PONs). Except for free-space optical communications (Section 1.5), most

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wireless access networks use RF signals to establish communication links between a central office and subscribers. In this section we discuss various broadband radio access technologies and their characteristics. The choice of radio access technologies depends largely on the applications, required data rate, available frequency spectrum, and transmission distance. Even though wireless access networks cannot compete with wired access technologies in terms of data rate and reliability, they offer flexibility and mobility that no other technologies can provide. Therefore, wireless access networks complement current wired access technologies and will continue to grow in the future.

1.7.1 Wi-Fi Mesh Networks

The Wi-Fi network based on IEEE 802.11 standards was developed in the 1990s for wireless local area networks, where a set of wireless access points function as communication hubs for mobile clients. Because of its flexibility and low deployment cost, Wi-Fi has become an efficient and economical networking option that is widespread in both households and the industrial world, and is a standard feature of laptops, PDAs, and other mobile devices. Now Wi-Fi is available in thousands of public hot spots, millions of campus and corporate facilities, and hundreds of millions of homes. Even though current Wi-Fi networks are limited primarily to point-to-multipoint communications between access points and mobile clients, multiple access points can be interconnected to form a wireless mesh network, as shown in Figure 1.7. The wireless access points establish wireless links among themselves to enable automatic topology discovery and dynamic routing configuration. The wireless links among access points form a wireless backbone referred to as *mesh backhaul*. Multihop wireless communications in mesh backhaul are employed to forward traffic to and from a wired Internet entry point, and each access point may provide point-to-multipoint access to users known as *mesh access*. Therefore, a Wi-Fi mesh network can provide broadband access services in a self-organized, self-configured, and self-healing way, enabling quick deployment and easy maintenance.

Over the years, a set of standards has been specified by the IEEE 802.11 working group, including the most popular 802.11b/g standards. Table 1.3 compares the main attributes of these standards (pp152, 3G Wireless with WiMAX and Wi-Fi). The original 802.11 standard (approved in 1997) supports data rates of 1 or

TABLE 1.3 Comparison of IEEE 802.11 Standards

Parameter	802.11a	802.11b	802.11g	802.11n	802.11y
Operating frequency (GHz)	5	2.4	2.4	2.4 and 5	3.7
Maximum data rate (Mb/s)	54	11	54	248	54
Maximum indoor transmission distance (m)	35	40	40	70	50
Maximum outdoor transmission distance (m)	100	120	120	250	5000

2 Mb/s using FHSS (frequency hopping direct sequence) with GFSK modulation or DSSS (direct sequence spread spectrum) with DBPSK (differential binary-phase shift keying)/DQPSK (differential quadrature-phase shift keying) modulation. In 1999, 802.11b extended the original 802.11 standard to support 5.5- and 11-Mb/s data rates in addition to the original 1- and 2-Mb/s rates. The 802.11b standard uses eight-chip DSSS with a CCK (complementary code keying) modulation scheme at the 2.4-GHz band. Also approved in 1999 by the IEEE, 802.11a operates at bit rates up to 55 Mb/s using OFDM with BPSK, QPSK, 16-QAM, or 64-QAM at the 5-GHz band. In 2003, IEEE ratified a newer standard, IEEE 802.11g, providing a 54-Mb/s data rate at the 2.4-GHz band. The 802.11g standard is back-compatible with 802.11b. The upcoming IEEE 802.11n standard will support a 248-Mb/s data rate operating at the 2.4- and 5-GHz bands. In addition, IEEE 802.11e provides effective QoS support, and IEEE 802.11i supports enhanced security in wireless LANs. Even though Wi-Fi networks based on IEEE 802.11a/g/n can provide data rates over 50 Mb/s, their maximum reach is very limited ($<$ 500 m). For last-mile solution, Wi-Fi mesh networks with multihop paths are necessary. However, due to RF interference, bit rates for multihop wireless communication could be much lower than the maximum data rate of a single wireless link. To support a long reach, IEEE 802.11y is currently under development for 54 Mb/s with a maximum reach of 5 km (outdoor environment).

In wireless networks, interference from different transmitters can be a serious problem limiting the throughput of the entire network. In Wi-Fi networks, MAC layer control uses a contention-based medium access called CSMA/CA (carrier-sense multiple access with collision avoidance) to reduce the interference effect and improve network performance. However, because of the randomness of data packet arrival time and the contentious nature of the MAC layer protocol, the throughput of Wi-Fi networks can be much lower than its maximum capacity.

1.7.2 WiMAX Access Networks

WiMAX access networks, based on IEEE 802.16 standards, can provide wireless broadband Internet access at a relatively low cost. A single base station in WiMAX networks can support data rates up to 75 Mb/s to residential or business users. However, since multiple users are served by a single base station, data payload delivered to end users is likely to 1 Mb/s for residential subscribers and a few Mb/s for business clients. Compared to the transmission distance of a few hundred meters supported by Wi-Fi (802.11a/b/g/n), WiMAX promises wireless access range up to 50 km. Therefore, WiMAX can provide citywide coverage and QoS capabilities, supporting multimedia applications from non-real-time data to real-time voice and video. Furthermore, as an IP-based wireless technology, WiMAX can be integrated seamlessly with other types of wireless or wireline networks.

The salient features of a number of 802.16 standards ratified by IEEE are shown in Table 1.4. The original IEEE 802.16 standrad defines backhaul point-to-point connections with bit rates up to 134 Mb/s using frequencies in the range 10 to 66 GHz, and IEEE 802.16d/e specifies point-to-multipoint wireless access at bit rates

TABLE 1.4 Comparison of IEEE 802.16 Standards

Parameter	802.16	802.16a	802.16e	802.16m
Operating frequency (GHz)	10−66	2−11	2−6	To be determined
Maximum data rate (Mb/s)	134	75	15	1000
Typical cell size (km)	2−5	7−10	2−5	Microcell (to be determined)

up to 75 Mb/s. The newest standard, IEEE 802.16m, supports data rates up to 1 Gb/s but with a much shorter transmission range.

Figure 1.10 shows the architecture of a typical WiMAX network. In WiMAX networks, WiMAX base stations are connected to the wireline networks (usually, optical metro networks) using optical fiber, cable, and microwave high-speed point-to-point links. Theoretically, a base station can cover up to a 50-km radius, but in practice it is usually limited to 10 km. The base station serves a number of subscriber stations (deployed at the locations of residential or business users) using point-to-multipoint links. A WiMAX network can be configured with a star topology or a mesh topology; each has advantages and disadvantages. Whereas star topology can support higher data rates, mesh topology provides a longer reach and faster deployment. The WiMAX MAC layer allocates the uplink and downlink bandwidth to subscribers according to their bandwidth needs. Unlike Wi-Fi networks, WiMAX networks adopt

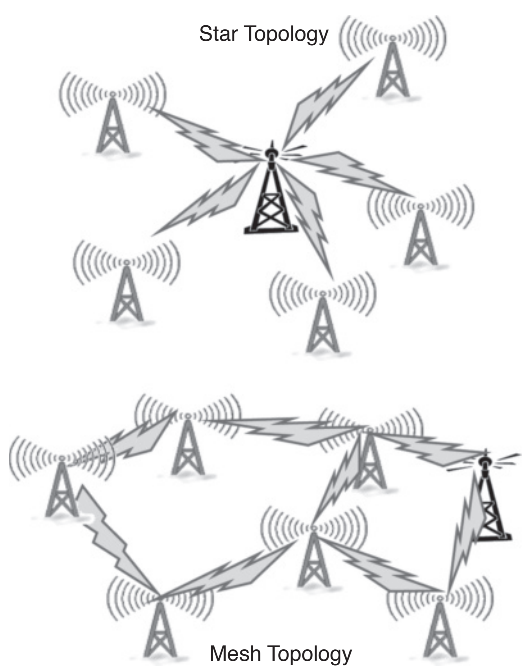

FIGURE 1.10 WiMAX network topology.

scheduled access using a time-division multiplexing technique, but the time slot assigned to each subscriber can vary in length depending on the bandwidth allocated to the subscriber. Because of the scheduling algorithm, WiMAX networks are more bandwidth efficient than are Wi-Fi networks.

1.7.3 Cellular Networks

During the last decade, cellular networks have spread all over the world, evolving from first generation (1G) to 2G and now moving toward 3G and 4G systems. The primary function of cellular networks is to carry voice communications for mobile users. However, as the telecom industry is migrating from voice- to data-centric networks, cellular networks have gradually built up their capacity for multimedia services such as data and video applications. As the first-generation cellular networks, AMPS (the Advanced Mobile Phone System) in North America and ETACS (the Extended Total Access Communication System) in Europe and Asia are analog, circuit-switched systems supporting only voice communications. The second-generation networks began the digital evolution. Digital encoding techniques such as CDMA, GSM, and TDMA pervade the cellular networks, and text messaging service becomes a common application. In addition, GPRS (general packet radio service) adds packet switching in GSM networks for high-speed data transmission (up to 171.2 kb/s), and EDGE (enhanced data rates for GSM evolution) further improved data transmission in GSM networks at bit rates up to 473.6 kb/s. The third-generation cellular networks based on UMTS (the universal mobile telecommunication system) or WCDM (wideband code-division multiple access) provide data service with bit rates above 144 kb/s. The emerging fourth-generation network will be an IP-based mobile system combining multiple radio access technologies, such as Bluetooth and wireless LAN, into an integrated network. The data rates supported by 4G networks could be as high as 100 Mb/s, thus providing truly broadband and ubiquitous access services.

Figure 1.11 illustrates the configuration of a typical cellular network, consisting of a base station controller, mobile switching center, base station transceiver, and mobile devices. To use the radio spectrum efficiently, the area covered by the cellular

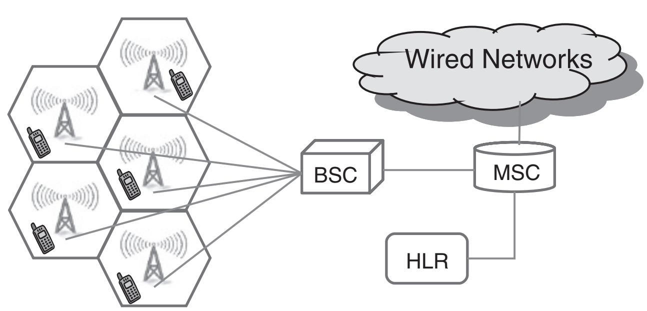

FIGURE 1.11 Cellular network architecture. MSC, mobile switching center; BSC, base station controller; HLR, home location register.

network is divided into small cells. Frequencies are reused in nonadjacent cells. Each cell has a base station that transmits and receives signals from the mobile devices within the cell. A group of base stations are connected to a base station controller. A group of base station controllers are in turn connected to a mobile switching center via microwave or fiber optic links. The base station controller controls communications between a group of base stations and a single mobile switching center. The mobile switching center connects to the public-switched telephone networks, which switch calls to other mobile stations or wired telephones. To provide data service, the mobile switching center is also connected to the Internet through edge routers.

Low-data-rate and incompatible technologies in current cellular networks (2G or 2.5G) present a serious problem for emerging multimedia applications. Hence, 3G networks have been developed to provide data rates over 1 Mb/s with a compatible radio interface among countries. However, economic concerns cast a doubt over large-scale deployment of 3G networks. Meanwhile, 4G technologies have emerged as a promising approach for mobile data service with a faster data rate than 3G. Despite all the efforts taken with developing data-centric cellular networks, broadband multimedia service over cellular networks still lags behind Wi-Fi and WiMAX networks in term of available bandwidth and network capacity.

1.7.4 Satellite Systems

Satellites have played an important role in providing digital communication links all over the world for a few decades. Originally developed for long-distance and intercontinental communications, satellites are also used for video broadcasting. Due to the development of VSATs (very small aperture terminals), satellite direct-to-home video broadcasting has been widely accepted since the mid-1990s. So far, satellite links have reached about 100 million homes, and widespread use of satellites for broadband access has become a reality. Satellite systems can cover a wide geographic area and support a variety of broadband applications, making it a very attractive broadband access solution. In fact, large corporate users have utilized satellite networks to establish wide area data networks to serve geographically dispersed corporate offices since the 1980s. A special type of satellite network called a *global positioning system* (GPS) has found popular applications for both military and civil navigation. Satellite operators for video broadcasting are dashing forward for broadband Internet access and multimedia applications.

Orbiting around the Earth, a satellite serves as a repeater and establishes a wireless link between any two users on the Earth. A satellite receives signals from Earth stations on an uplink, amplifies those signals, and then transmits them on a downlink with a different frequency. The first-generation satellites operate in the C-band, with a 4-GHz downlink and a 6-GHz uplink. However, large dish antennas have to be used for ground stations to improve receiver sensitivity and reduce microwave beamwidth. As bandwidth demands increase, the Ku-band (12/14 GHz for downlink/uplink) and Ka-band (20/30 GHz for downlink/uplink) were allocated by the U.S. Federal Communications Commission (FCC) for satellite communications. Using higher frequencies can support a higher data rate and permit the use of smaller-aperture antennas.

Recently, a higher-frequency satellite band, a V-band with a 40-GHz downlink and a 50-GHz uplink, has been approved by the ITU-T. With a V-band satellite, over 2 GHz of bandwidth is available, but atmospheric and rain attenuation become more severe at the V-band than at a lower-frequency band.

Modern communication satellites typically use a geostationary orbit with an orbital period matching the rotation period of the Earth. At a geostationary orbit, a single satellite can cover a huge geographical area (roughly 40% of the surface of the Earth). Since a geostationary orbit has a radius about 42,164 km, a long signal delay (about a 0.25 s round-trip delay) and large signal attenuation are unavoidable. Alternatively, low Earth orbit (200 to 2000 km orbital altitude) or medium Earth orbit (2000 to 3000 km orbital altitude) can be used with shorter delays and lower power attenuation. However, the coverage area of a low/medium-Earth-orbiting satellite is much smaller.

A satellite Earth station typically consists of a satellite modem, a transceiver, and an antenna. A parabolic reflector antenna is commonly used to transmit and receive satellite signals. A satellite transceiver includes low-noise frequency converters and power amplifiers made from microwave monolithic integrated circuits. A satellite modem performs data encoding and modulation. Since satellite links are mostly power limited, complicated encoding and modulation schemes are commonly used to trade bandwidth for better performance.

A set of open standards called DVB (digital video broadcasting) has been developed for digital television, including DVB-S, DVB-S2, and DVB-SH for satellite video broadcasting. However, these DVB standards specify that only point-to-multipoint one-way communication links be used for video broadcasting. With the growing demand for broadband access, two standards have been proposed to support two-way broadband communication links over satellites: DVB-RCS (return channel system) and DOCSIS-S. In DVB-RCS, the forward link (from the service provider to subscribers) is completely compatible with DVB-S. In other words, the forward link can be used for video broadcasting or Internet access. In addition, a return channel is specified for sending user data to the service provider, where ATM-like packets are used for data transmission. DOCSIS-S is an adaption of the DOCSIS standard for satellites. In DOCSIS-S, QPSK or SPSK, combined with turbo coding, is implemented for satellite links, and IP encapsulation is used for data transmission, resulting in more efficient bandwidth utilization and about 10% less overhead than with DVB-RCS.

1.7.5 LMDS and MMDS Systems

Local multipoint distribution service (LMDS), developed by the IEEE 802.16.1 working group, is a last-mile point-to-multipoint wireless access technology. Figure 1.12 shows the network architecture of LMDS systems. In the United States, a 1.3-GHz band between 28 and 31 GHz has been allocated for LMDS, whereas in Europe, LMDS may use different frequency bands from 24 to 43.5 GHz. LMDS can transmit 34 to 38 Mb/s of data covering the range 3 to 5 km. Therefore, multiple cells are

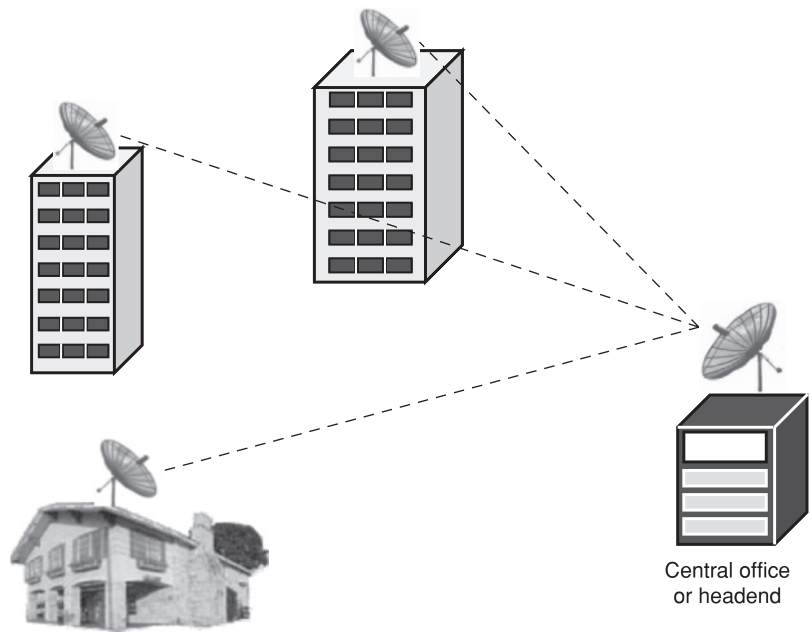

FIGURE 1.12 LMDS architecture.

usually required to serve a metropolitan area. In each cell, a base station with multiple transceivers mounted on the roof of a tall building or on a tall pole transmits users data in a point-to-multipoint mode. A return link from the user to the base station is achieved by a point-to-point link. Even though the physical layer is different from that of the wired cable networks, LMDS has adopted DOCSIS specifications.

Multichannel multipoint distribution service (MMDS), also known as *wireless cable*, was developed in the 1970s as an alternative to cable TV broadcasting. It can support 31 analog channels (6 MHz each) in a 200-MHz frequency band from 2.5 to 2.7 GHz. An MMDS system can also be used as a general-purpose broadband access network. MMDS has been deployed for wireless high-speed Internet access in rural areas where other types of broadband access are unavailable or prohibitively expensive. Figure 1.13 shows the architecture of an MMDS system. In an MMDS system, analog video signals or QAM/OFDM data signals are broadcast from microwave towers at the headend. At the user premises, rooftop antennas pick up the broadcast signal and downconvert it to cable channel frequencies. A gateway device is used to rout various signals to in-home network devices. Overall, the architecture of MMDS resembles that of LMDS. Similarly, MMDS systems have adopted DOCSIS specifications. DOCSIS modified for wireless broadband is commonly referred to as DOCSIS+. MMDS systems can provide a data rate of over 10 Mb/s to a single user. MMDS broadcasts can transmit signal power up to 30 W and cover a diameter of about 50 km, much more than LMDS systems.

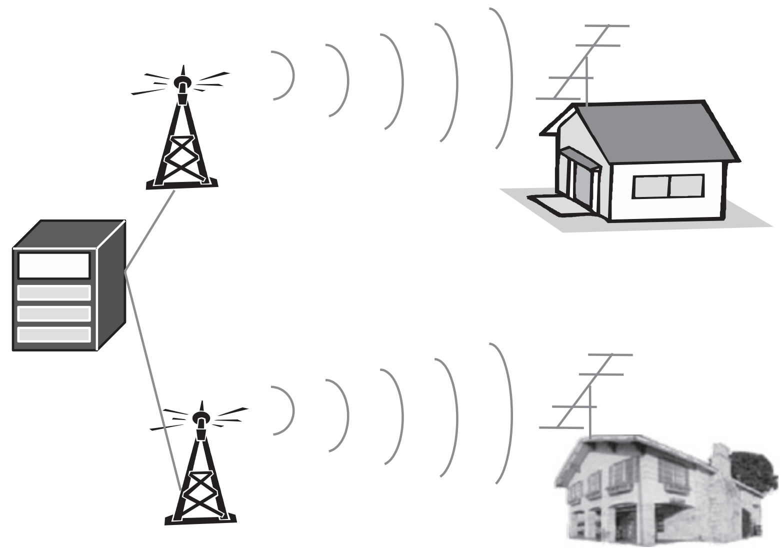

FIGURE 1.13 MMDS architecture.

In the past, even though DSL and cable dominated the broadband access market, LMDS and MMDS showed some promising aspects as wireless solutions. However, for both technical and marketing reasons, LMDS and MMDS systems were never widely adopted for broadband access. Now as WiMAX standards are developing, LMDS and MMDS are surpassed by WiMAX in both technical merit and market potential. Therefore, LMDS and MMDS may become obsolete in the near future.

1.8 BROADBAND SERVICES AND EMERGING TECHNOLOGIES

Broadband access technologies have shown explosive growth in large-scale deployment during the past decade. As of 2007, there are over 300 millions of broadband subscribers worldwide. In the United States alone, broadband Internet access has penetrated over half of U.S. households, reaching 66 million subscribers in 2007. The number of broadband subscribers will continue to grow in the years to come.

Today's broadband applications are mostly driven by Internet users—hundreds of millions of end users generating terabits per second of Internet traffic, and others by the entertainment industry—online or broadcasting video and music consuming a large portion of Internet traffic. The huge bandwidth demands impose a great pressure on broadband access, the technology bridging the gap between home and Internet backbone. Although it presents a great technical challenge, broadband access will lead to a great opportunity to develop new applications and services. In previous sections we have presented various broadband access technologies. Among these, DSL and cable are the dominant wireline access networks, and cellular networks and Wi-Fi hot spots represent the most widely deployed wireless access technologies. On the other hand, two versions of PON networks, GPON and EPON, become the most promising solution for future broadband services. In this section we review current market demands and driving forces for broadband access, discuss challenging issues in broadband access services, and present possible solutions for future broadband access technologies.

1.8.1 Broadband Access Services

The existing pressure from broadband services has led to heated competitions in access technologies and may shatter the current landscape of the telecom industry. There are a few driving forces behind this huge wave of broadband deployment. Multimedia applications, user bandwidth demands, industrial competitions, economical factors, and government regulation all play very important roles in the march toward "broadband for all" society. Multimedia applications create huge market demands for broadband access. Video services such as IP TV, video on demand, and videoconferencing, particularly, have become killer applications for bandwidth explosion in access networks. In addition to HD and standard TV broadcasting, video has consumed more than 30% of current Internet traffic, and this percentage keeps increasing. It is predicted that video traffic will consist of more than 50% of total Internet traffic. Because of peer-to-peer Web traffic (including video sharing) and other bandwidth-hungry applications (e.g., interactive games), user bandwidth demands are increasing rapidly, rendering broadband DSL and cable Internet access "slow speed." To meet user bandwidth demands and to support multimedia applications, both telecom and cable industries are deploying next-generation broadband technologies, including passive optical networks. Government deregulation, particularly local loop unbundling, has created heated competition in the access segment between telecom operators and MSOs and between ILECs (incumbent local exchange carriers) and IXCs (interexchange carriers). In addition, economical reasons for reducing OPEX (operating expenses) and increasing revenue create a big incentive for large-scale deployment of passive optical networks. Driving by market demands and technical innovations, broadband access networks will continue to evolve in the next few years.

Even though DSL and cable access have come to dominate broadband access in many countries, the broadband service currently offered by service providers is just an extension of existing technologies that provide data service. Telecom operators developed DSL to offer data service over phone lines, and MSOs added bidirectional transmission in HFC networks to support data transmission. *Triple play* has become a buzzword for service providers, but it is very difficult for DSL and cable access to offer triple play, due to their limited bandwidth. In addition to bandwidth, next-generation broadband access requires much more.

As communication networks is evolving toward anywhere, anytime, and any medium communications, future broadband subscribers may requires integrated access services over a unified interface with good end-to-end quality of service at a low service fee. Integrated services over the broadband access networks must be able to provide triple play or even quadruple play (voice, data, video, and mobility). Bandwidth over 100 Mb/s per user might be necessary to support triple play. Furthermore, good end-to-end quality of service is essential for many applications, and the broadband service must be dependable and available all the time. For real-time voice and video, there are tight constraints in delay and jitter. It might not be possible for a single technology to meet these requirements, but future broadband services must be available through an intelligent interface that is transparent to subscribers. No matter what service a subscriber might need, a single user interface will provide it with good QoS support. Finally, the access segment is always cost sensitive; service providers must be able to provide broadband for all service at a price comparable to that of current DSL or cable access.

1.8.2 Emerging Technologies

As discussed earlier, fiber is the only medium that can provide unlimited bandwidth for broadband access services. In the past, economics and lack of killer applications hindered its deployment in the access segment. As the optical technologies become mature, optical components are much less expensive and the fiber deployment cost continues to drop. It is now economically feasible to massively deploy passive optical networks. In the meantime, killer applications such as video on demand have emerged, demanding broadband access service that can be only supported by optical fibers in terms of bandwidth and reach. Since IP over WDM optical networks has been widely deployed in both WAN and MAN, it is not only reasonable but also necessary to deploy optical fibers to the user premises. In fact, different flavors of TDM PONs (mostly BPON and EPON) have been deployed on a large scale. Curently, Japan and Korea have taken the lead in FTTx deployment, and fibers have reached a large percentage of households, serving millions of users. In Japan, there are about 26 million broadband subscribers. Among these, 33% were using FTTH connections in 2007. Even though the majority of subscribers (about 50%) continue to use DSL, the market share of DSL has begun to shrink and FTTH continues to grow. In the first quarter of 2007, FTTH subscribers increased by 860,000 while DSL lost 220,000 users. In the United States, rapid deployment of passive optical networks began in 2005. In 2007, 2 million homes in the United States had fiber connections. FTTH networks will continue to grow all over the world. In Chapter 2 the fundamental of optical communications and the physical technologies for passive optical networks are discussed in detail. Then in Chapter 3, current TDM PON standards are reviewed and compared.

Next-generation optical access networks will evolve to higher bit rates and multiple wavelengths. Currently, 10-Gb/s PONs are being discussed by standard bodies (IEEE, FSAN, and ITU-T). 10-Gb/s downstream deployment include upstream bit rates of 1.25 or 2.5 Gb/s, and symmetric 10-Gb/s PONs will enter the market in the next few years. Eventually, optical access networks will adopt WDM technologies. The advantage of WDM PONs are higher bandwidth, flexible data format, and better security. However, point-to-point WDM access is relatively expensive despite the quick drop in the cost of optical components. Furthermore, a few issues, including protection and restoration and colorless ONUs, need to be addressed before WDM PONs become wide available. In the short term, hybrid TDM/WDM can provide an evolutionary approach to upgrade TDM to WDM PONs in a scalable and cost-effective manner. Next-generation optical access networks—higher-bit-rate, multiple-wavelength PONs—are the focus of Chapter 4.

Even though passive optical networks can satisfy any user bandwidth demands for triple play (voice, data, and video), their fixed infrastructure and limited coverage cannot fulfill the requirement of ubiquitous and flexible access for emerging multimedia applications. Due to recent advances in wireless technologies, wireless access networks such as Wi-Fi (IEEE 802.11) and WiMAX (IEEE 802.16) become a promising solution to serve the growing number of wireless subscribers interested in high-quality video streams and other multi-media applications using handheld mobile devices. In the future, convergence of optical and wireless technologies is inevitable in the access segment for quadruple play (voice, data, video, and mobility). However, as the traffic behavior and channel quality of these two technologies are far from each other, seamlessly integrating passive optical networks and wireless mesh networks present a very challenging task that demands further investigation. In Chapter 5 we present the challenging issues and possible solutions for hybrid optical and wireless networks.

1.9 SUMMARY

In this chapter we provide a brief overview of the architecture of communication networks and show that current Internet bottlenecks are due to the lack of high-speed access technologies. Then various broadband access technologies are discussed and the major features of DSL, HFC, PON, BPL, Wi-Fi, WiMAX, celluar and satellite networks, and LMDS and MMDS are presented in detail.

DSL can offer data rates over 10 Mb/s within a short distance. Efforts to develop next-generation DSL focus on increasing data rates and transmission distance. With DSL, voice and data can be supported by a single phone line. In the past decade, DSL has become one of the dominant broadband access technologies worldwide. However, TV broadcasting and IP TV are still a technical challenge for DSL networks. Using VDSL and advanced data-compressing techniques, video over IP may be offered in the near future.

Traditionally, HFC networks offer analog TV broadcasting. With the development of cable modem, broadband Internet access can be provided to subscribers. Cable is currently the archrival of DSL, claiming a large portion of market share. However, the bandwidth of coax cable access is still limited to about 10 Mb/s because of hundreds of users sharing the same cable. Currently, MSOs have added VoIP and digital TV over HFC networks. Further development will extend the cable plant beyond 1 GHz, and higher data rates will be the main focus of HFC networks.

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BPL is developed as an alternative for DSL and HFC networks. The data rate provided by BPL can reach only a few megabits per second. As power lines reach more residences than any other wired medium, BPL is considered a feasible access technology for rural areas that have no DSL and HFC access. However, technical problems such as noise and interference have hindered large-scale development of BPL.

As optical fibers can provide essentially unlimited bandwidth, PONs are considered the most promising wired access technologies for the future. Current TDM PONs support data rates of tens of megabits per second for a single user, and large-scale deployment of TDM PONs has begun in Asia and North America. As the user bandwidth demands are ever increasing, WDM PONs will be developed as the ultimate solution for broadband access and satisfy the bandwidth requirements of any broadband access services. However, the high deployment cost make them presently a less attractive solution. Current efforts on PON development include bit-rate enhancement and service overlay on hybrid TDM/WDM PONs.

In addition to wired broadband solutions, many wireless technologies have been developed to provide broadband Internet access, such as free-space optical communications, Wi-Fi, WiMAX, and cellular and satellite networks. Free-space optical communications can support gigabit per second data rates and a transmission distance of a few kilometers, but the atmospheric effects impose severe constraints for free-space optical communications. Wi-Fi is widely used for wireless local area networks with transmission distances up to a few hundred meters. With a mesh topology, Wi-Fi networks can support extended reach and broadband Internet access. WiMAX can support wireless access over 10 km, but it requires higher transmitted power and the data rate is lower than in Wi-Fi networks. Cellular networks are used primarily for mobile voice communication. With digital encoding technologies, data transmission service can be added over cellular networks but with a very limited data rate (up to a few Mb/s). Further development of 3G and 4G is expected to support much higher data rates over 10 Mb/s. Satellite networks are used primarily for direct video distribution, but data service over satellite can cover a large geographical area. The main disadvantage of satellite communication is that of very limited data rates. The advantages of wireless technologies are mobility, scalability, low cost, and ease of deployment. Except for free-space optical communication, other wireless technologies uses RF or microwave frequencies. The bit rate–distance product of RF technologies is very limited, and the network capacity and reliability are also much lower than these of wired access networks. In the future, optical and wireless technology may be combined in hybrid optical and wireless access networks, leveraging their complementary characteristics to provide quadruple-play service.

In summary, emerging multimedia applications demand broadband access networks, and a number of wired and wireless broadband access technologies have been developed over the past decade. The long-term perspective of broadband access technology lies in the convergence of optical and wireless technologies. By solving the last-mile bottleneck problem, a variety of new applications will be made possible. One day the dream of broadband access networks for anyone, anywhere, anytime, any medium communications will become a reality.

REFERENCES

1. DSL standards: ITU-T G.992.1/G.992.2 for ADSL, G.992.3/G.992.4 for ADSL2, G.993.1 for VDSL, G.993.2 for VDSL2, G.991.1 for HDSL, and 991.2 for SHDSL.
2. DOCSIS standards: ITU-T J.112 for DOCSIS 1.0, J.122 for DOCSIS 2.0, and J.222 for DOCSIS 3.0.
3. PON standards: ITU-T G.983 for APON and BPON, G.984 for GPON, IEEE 802.3ah for EPON, and 802.3av for 10GEPON.
4. BPL standards: X10 and IEEE P1675/1775/1901.
5. Wi-Fi standard: IEEE 802.11.
6. WiMAX standard: IEEE 802.16.