Chapter 1

# Introduction

*Cedric F. Lam*

*OpVista Inc.*

The recent surge in bandwidth demand, driven by fast-growing video-on-demand (VOD) services and emerging applications such as network gaming, peer-to-peer downloading etc. has revitalized the optical communication industry. After more than 20 years of active research, passive optical network (PON)-based broadband optical access systems are finally seeing wide-scale deployments in Asia and North America. In Europe, carriers and service providers are also actively looking into PONs as the next-generation broadband access solutions.

## 1.1 HISTORY OF BROADBAND ACCESS NETWORKS AND PON

Access networks have been traditionally called last-mile networks as they comprise the last segment connection from service providers' central office (CO) to end users. They are also called first-mile networks in recent years as they are the first segment of the broader network seen by users of telecommunication services. Example of access networks are twisted copper pairs connecting to each individual household (also called local loops) and residential coaxial cable drops from community antenna TV (CATV) service providers. Wi-Max is another type of access technology which uses radio waves for last-mile connectivity. Traditionally, optical fibers have been widely used in backbone networks because of their huge available bandwidth and very low loss. Although fiber has also been touted as the next-generation access technology for a long time, it is not until the beginning of this century that fiber has finally seen its growing commercial importance as the technology of last-mile connection.

Traditional telecommunication networks were developed for analog voice services. For a long time, 4 kHz was the bandwidth required to connect to end users for voice services. A ubiquitous twisted copper network has been deployed by telephone companies (the Bell System in the United States and PTTs in other countries) in industrialized countries for decades. It is not difficult to imagine that such networks were optimized for analog voice frequency transmissions. As a matter of fact, in order to achieve better economy and allow longer local loop drops, inductors called loading coils have been installed in many old twisted copper pair plants to enhance the voice frequency band performance. Loading coils, however, significantly attenuate high frequency signals outside the voice frequency band and make them unsuitable for broadband digital subscriber line (DSL) services.

Although voice signal transmission has been digitized into 64 kbps digital channel (DS0) for TDM switching long time ago, digital voice signals have been converted back to analog format to be backward-compatible with analog telephone sets before they are delivered to end users. The Internet is the driving force for digital local loops, also called DSLs [1]. The Internet was first invented in the 1960s. For a long time after its invention, the Internet was mainly used by research and academia for data sharing. The first popular Internet application was e-mail, which was invented in the early 1970s. It was not until the early 1990s, when the World Wide Web and its graphical user interface MOSAIC came out, that the Internet started to become an important part of people's lives. Because of the voice bandwidth limitation and transmission line noise, the best data rate available from an analog modem working on voice grade twisted copper lines is 56 kbps.

### 1.1.1 Digital Subscriber Line (DSL)

The first broadband DSL standard was the integrated services digital network (ISDN) system developed in the 1980s by CCITT which was the predecessor of ITU-T. The ISDN (also called IDSL) standard offers the so-called 2B + 1D encoding scheme on a single twisted pair. It includes two 64-kbps (2B) channels for voice and data, and one optional 16-kbps (1D) digital channel. This gives a total of 144 kbps data rate in both directions. ISDN services were never popular because of the high cost and lack of killer applications.

As web pages incorporate more and more multimedia data, the demand for bandwidth is slated to grow in order to satisfy customer expectations. Various flavors of DSL technologies (collectively called xDSL) have been invented for broadband data delivery on twisted copper pairs. DSL services make use of the higher frequency range on twisted pairs for data transmission. The 0- to 4-kHz band carries the traditional plain old telephone service (POTS) line. Typically, the 25- to 160-kHz band carries the upstream (user to carrier) direction data and the 240-kHz to 1.5-MHz band carries the downstream (carrier to user) direction data.

DSL data rates and transmission distances are limited by signal impairments inside twisted copper pairs [2]. The attenuation of electromagnetic waves on copper wires increases as the square root of the signal frequency. Therefore, higher frequency signals attenuate faster on twisted pairs. The aforementioned loading coils on old twisted pair plants must be removed in order to offer DSL services. Moreover, copper wire quality, bridge taps on twisted pairs, and cross talk between neighboring twisted pairs all degrade the signal quality.

Most of the DSL technologies today use a modulation technique called discrete multitone modulation (DMT), which divides the whole frequency bands into 247 channels of 4-kHz slots. Signal quality in each slot is constantly monitored and the signals are shifted from bad slots to good ones in an adaptive manner.

Asymmetric DSL (ADSL) and very high data rate DSL (VDSL) are the two most common DSL services. ADSL provides a downstream data rate of up to 8 Mpbs and upstream data rate up to 800 kbps, over a maximum transmission distance of 18000 ft or 5500 m. VDSL services are usually supported with a fiber deep infrastructure such as fiber-to-the-curb (FTTC), which has a short distance of twisted copper loop. For a 4000-ft (1200-m) twisted pair drop distance, VDSL can support up to 52 Mbps and 16 Mbps downstream and upstream data rates respectively. Table 1.1 gives a summary of the different DSL technology performances.

To receive DSL services, typically, users need to install a filter to separate the voice signal from data signals. A DSL modem is employed at the user end to connect the user to the service provider through a DSL access multiplexer (DSLAM), which is located at a remote node or CO. The DSLAM provides point-to-point dedicated bandwidth between the service provider and each end user. This scenario is different from the cable modem and PON scenarios described later.

### 1.1.2 Cable Modem

Traditional CATV networks were one-way broadcast systems. CATV programs are transmitted as analog signals in amplitude modulation–vestigial side band (AM-VSB) format [3]. Each CATV channel occupies a 6-MHz frequency division multiplexed (FDM) frequency slot in the North American National Television System Committee (NTSC) standard or 8-MHz slot in the phase alternate line (PAL) standard used in other parts of the world. Broadcast TV signals normally occupy a frequency band from 50 MHz to 500 MHz or 750 MHz.

**Table 1.1**
**Summary of different DSL technology performances**

| DSL type | Max Speed Upstream | Max Speed Downstream | Max transmission distance | Number of lines required | POTS support |
|---|---|---|---|---|---|
| ADSL (asymmetric DSL) | 800 kbps | 8 Mbps | 18,000 ft (5500 m) | 1 | Yes |
| HDSL (high data rate DSL) | 1.54 Mbps | 1.54 Mbps | 12,000 ft (3650 m) | 2 | No |
| IDSL (ISDN) | 144 kbps | 144 kbps | 35,000 ft (10700 m) | 1 | No |
| MSDSL (multirate symmetric DSL) | 2 Mbps | 2 Mbps | 29,000 ft (8800 m) | 1 | No |
| RADSL (rate adaptive DSL) | 1 Mbps | 7 Mbps | 18,000 ft (5500 m) | 1 | Yes |
| SDSL (symmetric DSL) | 2.3 Mbps | 2.3 Mbps | 22,000 ft (6700 m) | 1 | No |
| VDSL (very high data rate DSL) | 16 Mbps | 52 Mbps | 4000 ft (1200 m) | 1 | Yes |

Linear optical transmission system has been used for analog TV signal transmission. CATV signals are transmitted from service providers' headend[1] offices to remote fiber nodes (called hub nodes) where they are converted back to the radio frequency (RF) domain and transmitted through coaxial cables to end users. Therefore, CATV systems are also called hybrid fiber coax (HFC) systems. Coaxial cable plants are laid out in a tree-and-branch architecture with cascaded RF amplifiers. Compared to twisted pairs, the coaxial cable is a very good

[1] CATV service providers have different terminologies than traditional telecommunication service providers. Some of the terminologies could be confusing between CATV and telecommunication service providers. A cable headend is called a central office or core node by telecommunication service providers. It is usually located directly on the backbone. Telecommunication service providers also call their core backbone nodes hubs, and small distribution nodes edge node. However, a hub node for CATV providers is a local signal distribution node, which parallels telecom service providers' edge nodes.

broadband medium with excellent frequency responses. It has a usable frequency range up to 1 GHz.

In North America, CATV service providers also call themselves multiple service operators (MSOs). In the mid-1990s, MSOs started to reform their traditional one-way analog broadcast systems by putting in bidirectional RF amplifiers and return optical links so that they can provide data and other services such as VOD. The 1996 Telecom Act [4] in the United States liberalized the telecommunication service market. MSOs took advantage of their coaxial cable to offer broadband data services through cable modems.

Unlike the rest of the world, where DSL services are far more popular than cable modem, in the United States, cable modem was the dominating form of broadband access for several reasons. Firstly, the coaxial CATV plant coverage in the United States is far more complete than in other countries. The majority of households are connected to MSO providers through coaxial cable drops. Secondly, being the first nation with ubiquitous telephone service deployments, most of the twisted pairs in the United States were too old, too long, and too poor in quality to enable DSL services. Thirdly, the data over cable service interface specification (DOCSIS) [5] 1.0 released in March 1997 made significant contribution to the success of cable modem in the United States by offering a common specification for multivendor interoperability and therefore helped to lower the equipment and service costs.

DOCSIS standards are developed by Cable Labs. In a cable modem system, cable modems at individual households are connected to a cable modem termination system (CMTS) at a headend office. The tree-and-branch coaxial cable plant forms a shared medium among the cable modem users. Customer data are multiplexed using the time division multiplexing (TDM) scheme. Downstream data signals from headends are broadcast to individual cable modems through the coaxial cable plant. Each individual cable modem recognizes its data by the ID embedded in downstream data. The CMTS acts a medium access control (MAC) master which assigns upstream time slots for each cable modem. This is very different from DSL systems where a dedicated line is provided between a DSL modem and the DSLAM.

Cable modems use the 0- to 45-MHz frequency band in the coaxial cable for upstream transmission. This frequency range usually has poorer channel characteristics due to the coupling from sources such as home electrical appliances. Another source of degradation in the upstream band is due to the noise funneling effect from all the upstream users.

DOCSIS specified a modulation technique called quadrature amplitude modulation (QAM) [6], which encodes multiple bits of information on each symbol. For example, on a 256-QAM channel, each symbol represents 8 bits ($\log_2 256$) of information, so that a 5-MSps (mega symbol per second) channel can carry a 40-Mbps data stream. DOCSIS 1.0 specified channel widths between

200 kHz and 3.2 MHz. 64-QAM and 256-QAM are used for downstream modulation. For upstream connections, quadrature phase shift keying (QPSK, which is equivalent to 4-QAM) and 16-QAM are used. This gives an upstream and downstream throughput of 10 Mbps and 38 Mbps respectively. DOCSIS 2.0 [5] increased the upstream capacity by employing 32-, 64-, and 128-QAM.

To cope with increasing bandwidth demand from customers, DOCSIS 3.0 [5] further increased the available data bandwidth to above 100 Mbps in both directions through a technique called channel bonding. Significant performance improvement is achieved by bonding 4 RF channels as a single logical data channel. Table 1.2 summarizes the data rates of different DOCSIS versions. Different versions of the DOCSIS protocols have been made backward compatible.

Although the maximum cable modem throughput can reach 38 Mbps downstream and 10 Mbps upstream in DOCSIS 1.0, most MSOs throttle the maximum data rate from users from 3 Mbps to 8 Mbps downstream and from 200 kbps to 800 kbps upstream because of the shared nature of the cable modem bandwidth. Higher rates are also available to users who are willing to pay premium prices. Per user available bandwidth can be improved by shrinking the sharing group size, i.e. decreasing the size of each coaxial tree by pushing fiber deeper into the field. In modern HFC systems, the share group size is usually between 50 and 100 households per fiber node [7].

The cable modem architecture has a lot of similarities to the most commonly seen power-splitting PON architecture, although they use completely different media for transmission. Both cable modem system and power-splitting PON use a point-to-multipoint (P2MP) tree-and-branch distribution plant as shared transmission medium among all the end nodes. They both use TDM for MAC. In a cable modem access system, the CMTS and cable modem form a master–slave relationship for medium control. The CMTS controls the bandwidth allocation to cable modems. In a power-splitting PON, the optical line terminal (OLT) and optical network unit (ONU) form a master–slave relationship for medium control. The OLT controls bandwidth allocation to the ONUs. Dynamic bandwidth allocation (DBA) is required in both cable modem systems and power-splitting PONs.

**Table 1.2**

**Summary of DOCIS data rates**

| DOCSIS version | Max data rate: Downstream | Max data rate: Upstream |
|---|---|---|
| 1.0 | 38 Mbps | 10 Mbps |
| 2.0 | 40 Mbps | 30 Mbps |
| 3.0 | 160 Mbps | 120 Mbps |

### 1.1.3 Fiber Access Systems

Local loops using optical fiber for access connections are called fiber-in-the-loop (FITL) systems [8–9]. Optical fiber has the advantage of high bandwidth, low loss, and low noise. Compared to the coaxial cable plant, which usually requires many cascaded RF amplifiers, fiber plants are in general much cleaner and require very little maintenance.

Studies for FITL started in the 1980s [10–11]. Fiber access systems are also referred to as fiber-to-the-x (FTTx) system, where "x" can be "home," "curb," "premises," "neighborhood," etc., depending on how deep in the field fiber is deployed or how close it is to the user. In a fiber-to-the-home (FTTH) system, fiber is connected all the way from the service provider to household users. In an FTTC system, fiber is connected to the curb of a community where the optical signal is converted into the electrical domain and distributed to end users through twisted pairs. Therefore, an FTTC system can also be regarded as a hybrid fiber twisted pair system.

Nowadays, most people think of FTTx as the P2MP power-splitting PONs (PS-PONs). In reality, fiber access systems can be point-to-point (P2P) or P2MP. Moreover, they can use an active remote distribution node such as an Ethernet switch or a simple passive splitter as the remote distribution node used in PS-PONs. In fact, NTT adopted P2P architectures in some early FTTH trials [12]. Another type of PON called WDM-PON uses a wavelength multiplexer as the remote distribution node [11]. PON architectures will be described in detail in Chap. 2.

Although FITL was in trial for a long time since its proposal, the high cost of fiber-optic components and lack of killer applications for the high bandwidth offered by optical fibers have been barriers to its real applications. The PON architecture was proposed as a way to share the large fiber bandwidth among many users through a passive splitter, and hence improve the per user cost of FITL.

PON standardization work began in the 1990s when carriers anticipated fast growth in bandwidth demands. In 1995, the full service access network (FSAN) [13] consortium was formed by seven global telecommunication operators including British Telecom, NTT, and Bell South to standardize common requirements and services for a passive optical access network system. One of the goals of FSAN was to create the economy of scale and lower the cost of fiber-optic access systems by promoting common standards.

FSAN recommendations were later adopted by the International Telecommunication Union (ITU) as the ITU-T G.983 BPON (i.e. broadband PON) standards [14–16]. G.983 specified 622 Mbps downstream and 155 Mbps or 622 Mbps aggregate upstream data rate. Each OLT is shared by up to 32 ONUs for a maximum separation of 20 km between the OLT and ONU.

BPONs use TDM for multiple access and asynchronous transfer mode (ATM) cells for data framing. Therefore, a BPON is also called an ATM PON or APON for short.

The G.983.3 standard [16] specified wavelength division duplex on a single fiber with 1.3-μm wavelength for upstream transmission and 1.49-μm wavelength for downstream transmission. The 1.55-μm wavelength window was reserved for analog TV signal overlay. Early BPON standard defined the reference architecture model and the physical medium dependent (PMD) layer. But it also left many of the control and management message formats unspecified for a considerable while.

BPONs only had limited trials and deployments. In the past few years, Ethernet emerged as the dominating framing technology for packetized IP data transmission. In March 2001, the IEEE 802.3 standard group started the 802.3ah Ethernet in the First Mile (EFM) project [17]. One of the charters of the 802.3ah work group was to standardize the transport of Ethernet frames on P2MP PONs or EPON. The IEEE802.3ah Standard was ratified in June 2004. It specifies an upstream and downstream throughput of 1 Gbps and a transmission distance of 10 km or 20 km with 16 ONUs per OLT.

EPON has gained tremendous popularity in East Asian countries, especially Japan and Korea. NTT has selected EPON as the standard for its large-scale FTTH rollout [12]. Nevertheless, EPON did not achieve much commercial success in the United States.

At the same time that EPON was developed by IEEE, the ITU-T Study Group 15 (SG15) was also working on the next-generation PON called Gigabit-capable PON (G-PON). G-PON specifications are captured in the G.984 series recommendations [18–20]. G-PON increased the transmission speed to 2.5 Gbps downstream and 1.25 Gbps or 2.5 Gbps upstream. Besides, it uses a new framing mechanism called G-PON encapsulation mode (GEM), which is based on the original idea of generic framing procedure (GFP).

G-PON was selected as the standard by Verizon, SBC (now AT&T), and Bell South in January 2003 when the three incumbent telecommunication operators issued a joint request for proposal (RFP) for fiber-to-the-premise (FTTP). These companies will use G-PON to compete with MSOs in delivering the so-called triple-play (video, voice, and data) services.

### 1.1.4 Ethernet

Ethernet was invented in the 1970s [21]. It was originally invented as a local area network technology for interconnecting desktop computers. Ethernet has been firmly established as the standard user interface of choice for connecting IP devices. More than 90% of the IP packets are generated and terminated as

Ethernet frames.[2] Ethernet covers the bottom two layers (i.e. physical layer and data link layer) of the OSI reference model. It is standardized by the IEEE802.3 standard group. Figure 1.1 shows the development trend of the Ethernet technology and local area networks.

Because of its high bandwidth, low cost, and ease of use and installation, Ethernet has become the most popular technology for data networking. After the Internet boom, the amount of IP data traffic in telecommunication networks has greatly surpassed that of the traditional TDM voice traffic. Such traffic begins and terminates as Ethernet frames. Moreover, video streaming services are also moving on to IP-based digital platforms. New video servers stream both broadcast and on-demand TV signals as Ethernet packets. Efficient handling of Ethernet packets is therefore very important in next-generation networks.

The first-generation Ethernet used MAC protocol called Carrier Sense Multiple Access with Collision Detection (CSMA/CD) for local area networking [22]. All the hosts are connected in a multipoint-to-multipoint (MP2MP) coaxial

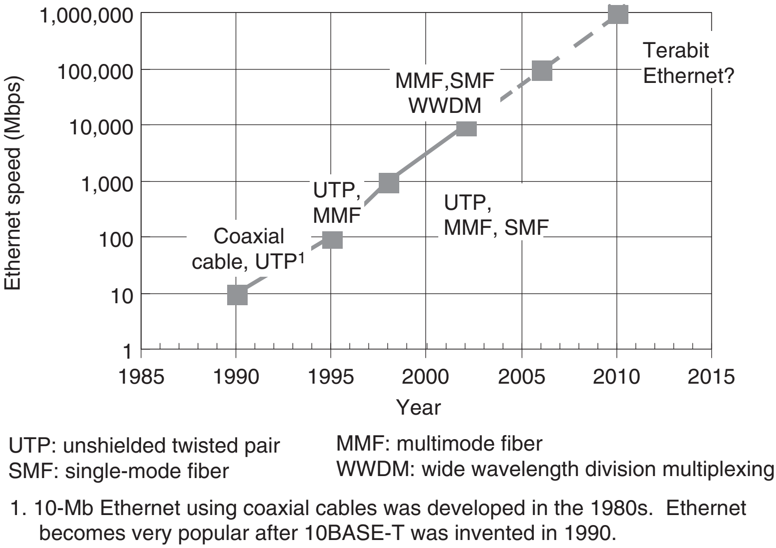


**Figure 1.1** Development trend of Ethernet technologies.

2 In switched networks, protocol data units (PDUs) on Layer 3 of the ISO reference model or the IP layer are usually referred to packets. Layer 2 or Ethernet protocol data units are usually called frames. These two terms are often used interchangeably.

bus line. Each station can directly communicate with another station in a peer-to-peer fashion. The CSMA/CD protocol is completely distributed. It does not require a master controller for bandwidth arbitration on the transmission medium. However, the CSMA/CD protocol also limits the transmission speed and distance. As the data rate increases, the network size has to be scaled down accordingly.

The transmission distance limit imposed by the CSMA/CD protocol was removed when full-duplex Ethernet was introduced. In a modern full-duplex Ethernet, all the stations in the network communicate with each other through a P2P link to a switch (also called bridge). Switches perform medium arbitration among connected stations and relay packets from station to station in a transparent fashion (i.e. connected stations have no knowledge of the existence of switches).

Ethernet switch operations are specified in the IEEE802.1 Spanning Tree Protocol (STP) [23]. STP is very important to full-duplex mode Ethernet operation, which removes the CSMA/CD protocol-imposed distance limitation. It allows Ethernet frames to be transmitted to distances only limited by the physical channel impairments such as noise and attenuation. To understand the principle of modern Ethernet, one really needs to have knowledge of both IEEE802.3 and 802.1 standards.

EPON created a new P2MP Ethernet architecture which is different from the original MP2MP and P2P models. For this reason, a P2P emulation function has been introduced in EPON in order to operate with the 802.1-based Ethernet switching.

Whether a PON system uses Ethernet (as in EPON), ATM (as in BPON), or GEM (as in G-PON) for data encapsulation between the OLT and ONU, there is no doubt that Ethernet is a must-support user network interface (UNI) that an ONU has to provide for connecting to customers' network equipment.

In the last few years, Ethernet has quickly moved out from the local area networks into backbone networks. End-to-end private-line Ethernet services are becoming more and more popular. Traditional Ethernet delivers best-effort services and lacks the capabilities of their TDM rivals such as SONET for management. The IEEE802.3ah EFM standard added an operation, administration, and management (OAM) sublayer to Ethernet. However, the OAM sublayer is mainly focused on a limited subset of performance monitoring functions of the physical and link layers.

To actually provide Ethernet services, the carrier must have the capability to control and manage Ethernet connections. Metro Ethernet Forum (MEF) [24], an industry consortium formed to promote Ethernet services, has been carrying out the effort of specifying Service Level Agreement (SLA) and OAM for carrier Ethernet. Other standard organizations such as ITU and Internet Engineering

Task Force (IETF) have also invested many efforts to make Ethernet more manageable and suitable for end-to-end service delivery.

### 1.1.5 WDM in Optical Access Networks

Wavelength division multiplexing (WDM) increases system capacity by transmitting multiple wavelengths on a single fiber. Coarse WDM techniques have already been applied in PON systems to separate upstream and downstream signals, and provide analog video overlay [16]. An important advantage of the optical fiber is its virtually unlimited bandwidth from an access viewpoint. Coarse WDM overlay on a power-splitting PON is an obvious way to provide different services and increase system capacity. For example, one can segregate the optical spectrum into different coarse WDM bands and engineer a G-PON system in one wavelength band and an EPON in a different band, doubling the value of the costly fiber plant [25].

All the PON systems mentioned so far use a power coupler to distribute the signal from OLT to users at different ONUs. In a WDM-PON system, a WDM coupler is used to distribute signals to different users. Each ONU is allocated with its own wavelengths. Such a system has the advantage of high capacity, privacy, and protocol transparency. The idea of WDM-PON was first proposed by Wagner and is now in field trial in Korea by Korea Telecom.

By using a wavelength cyclic (or so-called colorless) AWG device, one can spawn or realize multiple WDM-PON networks on a single physical fiber plant. The challenge of WDM-PON is wavelength stability control and low-cost colorless optical sources for the ONUs. A lot of research has been done in these areas to produce practical colorless AWG devices which are temperature-compensated, and colorless sources using ideas of injection locking a Fabry–Perot laser diode or reflective semiconductor optical amplifiers (RSOAs). Chapter 3 will describe these technologies in more detail. It is a matter of time before these devices will eventually become readily available when bandwidth requirement reaches the point at which WDM-PON systems will be necessary to satisfy customer demands. WDM-PON should enable broadband optical access network to stay passive for a considerable while before optical access networks eventually become active.

### 1.1.6 Killer Applications

The field of telecommunications took a significant dive in the beginning of this century because of the exuberance in capacity deployment. After some years of stagnancy, demands for bandwidths are growing again, and have become the driving force for the recent enthusiasm in PONs and FTTx developments.

It would be interesting to know that e-mail and the World Wide Web were the first and second killer applications in the history of the Internet since it was proposed in the 1960s. The Internet has been touted as the bandwidth driver in modern telecommunication networks. A slew of new applications have emerged in the past few years. Examples of these include peer-to-peer networking, sharing of music and video clips, network gaming, and voice-over IP.

Among all the emerging applications, the most important is the widespread adoption of digital TV and VOD. Digital TV signals are much easier to transport than analog ones because of the much lower linearity and signal-to-noise ratio requirements. From a technical viewpoint, VOD services have now become feasible because: (1) new mpeg video compression technologies have tremendously reduced the bandwidth and capacity required for digitized video transmission and storage; (2) electronic memory, storage, and processing technologies have made it possible to store and switch thousands of movies in practical-size video servers; and (3) low-cost WDM, Gigabit, and 10Gigabit Ethernet transmission technologies have enabled economical transport of high bandwidth video signals. For example, a Gigabit Ethernet link is capable of carrying 240 streams of standard resolution video signals in mpeg-2 format [26], each of which requires 3.5 Mbps bandwidth compared to the 200 Mbps per channel used in the last-generation digital video broadcast–asynchronous serious interface (DVB-ASI)-based digital TV systems.

From a business perspective, benefited from continual improvements of access bandwidths, the Internet has become an important new form of media in people's lives. The billion-dollar acquisition of YouTube by Google in 2006 is a clear reflection of such developments. In order to compete with the Internet, cable companies are busy reviving their services with VOD programs using IPTV technologies. In addition, in order to reduce both the capital and operational expenditures, carriers are merging their video and data delivery platform into a unified platform based on IP technologies. VOD has become the killer application for broadband access network development.

## 1.2 ECONOMIC CONSIDERATIONS IN PON DEVELOPMENT

### 1.2.1 How Much Bandwidth Is Enough?

An old question often asked is: "how much bandwidth will be enough for an end user?" The demand for bandwidth is driven by the contents available on the network, which is only limited by imagination. Capable technologies will find

**Table 1.3**

**Bandwidth requirements for different IP services**

| Application | Bandwidth | QoS |
|---|---|---|
| Video (SDTV) | 3.5 Mbps | Low loss, low jitter, constant bit rate |
| Video (HDTV) | 15 Mbps | Same as above |
| Telecommuting | 10 Mbps | Best effort, bursty |
| Video gaming | 10 Mbps | Low loss, low jitter, bursty |
| Voice | 64 kbps | Low loss, low latency, constant bit rate |
| Peer-to-peer downloading | 100 kbps–100 Mbps | Best effort |

their applications through people's creativity. The Internet was nothing new when the World Wide Web was invented in the early 1990s. Since then it has changed the way people live within a few years.

We also saw that the general availability of applications such as VOD happens naturally when a number of techno-economical factors come together. Without affordable broadband networks, even when compression and storage technologies are perfected, there will be no VOD services. Instead of speculating how much bandwidth is enough, we just summarize the bandwidth requirements for different applications in a typical household in Table 1.3.

A sustained connection of 100 Mbps will allow an 8-GB DVD movie to finish downloading in about 10 minutes, which will be comparable to the time taken to go to the video rental store at the next block. It is not difficult to imagine the requirement of 100 Mbps per broadband household. In fact, capacity is a major consideration when the RBOCs issued their joint G-PON RFP for FTTP applications in January 2003.

## 1.2.2 Policy and Regulation Influence

Communication network deployment requires significant upfront capitals. Whenever possible, companies would always like to evolutionarily upgrade their legacy infrastructure and maximize the value of existing investment.

Unlike in the United States, in most of the Asian countries government restrictions exist for telecommunication service providers to offer content services such as streaming video [27–28]. Nevertheless, countries such as South Korea and Japan have made significant progress in broadband access networks as a result of government incentives for new technology development. Percentage wise, Korea has the most broadband coverage in the world, whereas Japan accounts for two-thirds of global FTTH users.

In North America, continual deregulation of the telecommunication industry introduces fierce competition between MSOs and incumbent Regional Bell Operation Companies (RBOCs). New regulations allow MSOs and RBOCs to enter each other's traditional markets.

MSOs have not only finished converting their legacy one-way broadcast coaxial cable network into a bidirectional network, but are also taking the advantage of their broadband HFC network to provide high-speed data, digital TV, and voice services. Faced with the competition from MSOs and the rapid price erosion of their legacy voice services, RBOCs need to upgrade their 100-year-old twisted copper access plant in order to match or surpass services offered by MSOs. A fiber deep access network architecture or FTTx is the natural choice to future-proof their new investment.

In the United States, one of the incentives for RBOCs to build up fiber deep infrastructure is to bypass the requirement to share their access loops with competitors. In order to introduce competitions into the telecommunication market, the US government requires traditional incumbent carriers to unbundle (open) their twisted pair access loops to their competitors. Such requirements, however, do not apply to new access infrastructure investment such as FTTx.

### 1.2.3 Standardization Efforts

The DOCSIS [5] standards jointly developed by the cable industry had been a key factor for the success of the cable modem market in the United States by creating common multivendor interoperable specifications, and hence the necessary economy of scale.

The joint RFP from the US RBOCs in 2003 was aiming at recreating the DOCSIS story in the PON field. FSAN and ITU are the standard organizations responsible for the G.983 series BPON and G.984 series G-PON standards. These two organizations are also hosting interoperability test events among vendors manufacturing BPON and G-PON equipment.

The IEEE 802.3 standard group is responsible for EPON developments. This group traditionally had a good track record of keeping track of the details in technical requirements to ensure interoperability.

### 1.2.4 Cost Considerations

As mentioned in the beginning, although PON has been invented for over 20 years, it has not been commercially successful until recently. An access system connects end users to COs through local loops in two ways. The straightforward approach is to run a separate pair of wires (called home run) from each end user to the assigned CO. Alternatively, local loops first connect end users to a remote terminal (RT), which multiplexes the individual signals on a feeder line. The feeder line in turn connects to a local CO. Feeder lines provide pair gain by reducing the amount of wires required to connect each user to the CO.

There is trade-off between the cost of electronics in the RT and the savings achieved from the pair gain. If the cost of RT is high, in general, more users are required to share the cost, and the length of local loops will tend to be longer. The local loop distance where the cost of RT starts to make economic sense is called prove-in distance. Prove-in distance reduces as electronic technologies improve. In a PON system, the RT is simply a passive optical power splitter or WDM coupler.

It should be realized that lack of killer applications was not the reason for the slow adoption of the PON technology. In order for PON to become commercially viable, the cost of running a fiber local loop (labor + capital) needs to be in par with that of running a twisted pair loop, which is about $1000 in the United States. For a considerable period of time, fiber-optic components accounted for a significant portion of PON deployment cost. The high cost of optical components was the main barrier for FTTH deployments.

In order to improve the economic model of fiber access networks, instead of pulling fiber all the way to the home, PON systems have been proposed for various FTTx applications where the ONU is placed at a curb or building basement so that it can be shared by a group of users through a short drop of twisted pairs. The cost of optical components has come down significantly in recent years and FTTH is now making a lot of sense for high bandwidth broadband access.

PON belongs to access networks. Access equipment is usually deployed in large volumes. They are therefore very cost-sensitive. In a PON system, the cost of ONU needs to be multiplied by the number of users. This cost is either borne by the service provider or the end user. Therefore, low cost is the most important consideration in ONU designs.

## 1.3 ORGANIZATION OF THE BOOK

This book consists of seven chapters, covering different aspects of PON technologies.

Chapter 1 begins with the history of broadband access network and PON developments. It also discusses the economical and policy forces behind broadband infrastructure developments.

Chapter 2 reviews the various PON architectures and technologies. It paves the way to understand the reasons and philosophies behind the PON technology development, which will be covered in the ensuing chapters.

Chapter 3 thoroughly covers PON-related optical technologies and their state of the art.

Chapter 4 focuses on the properties and characteristics of PON transceivers, which are quite different from those used with conventional two-fiber, continuous-mode optical transmission systems.

Chapter 5 reviews the ranging process and dynamic bandwidth allocation protocols, which are essential to the operation and performance of power-splitting TDM PON systems.

As the PON speed and service group size increases, reliability and availability becomes more and more important. Chapter 6 discusses protection switching and traffic restoration schemes for PON systems.

A PON system differs from the traditional fiber-optic system in its P2MP and one-fiber bidirectional transmission architecture. Chapter 7 studies the challenges to characterize, monitor, and diagnose optical links in a PON system.

It is our wish to present this book as a comprehensive reference of PON technologies for those interested in developing and understanding this fast-growing area.

# REFERENCES


[1] K.G. Coffman and A.M. Odlyzko, "Growth of the Internet," in *Optical Fiber Telecommuncations IV B*, edited by I. Kaminow and T. Li, pp17–59, Academic Press, 2002.

[2] J.A.C. Bingham, *ADSL, VDSL and Multicarrier Modulation*, John Wiley & Sons, 2000.

[3] W.I. Way, *Broadband Hybrid Fiber/Coax Access System Technologies*, Academic Press, 1999.

[4] Federal Communications Commission, *Telecommunications Act of 1996*, available from http://www.fcc.gov/Reports/tcom1996.pdf and http://www.fcc.gov/telecom.html

[5] Cable Labs, Data Over Cable Service Interface Specification (DOCSIS), available from http://www.cablemodem.com/specifications/

[6] J.G. Proakis, *Digital Communications*, 3/e (Chap. 4), McGraw-Hill, 1995.

[7] O.J. Sniezko, T. Warner, D. Combs, E. Sandino, X. Lu, T. Darcie, A. Gnauck, S. Woodward, and B. Desai, "HFC Architecture in the Making," *NCTA Technical Papers*, 1999.

[8] N.J. Frigo, "A survey of fiber optics in local access architectures," in *Optical Fiber Telecommunications, III A*, edited by I. Kaminow and T.L. Koch, pp461–522, Academic Press, 1997.

[9] E. Harstead and P.H. van Heyningen, "Optical Access Networks," in *Optical Fiber Teclecommunications, IV B*, edited by I. Kaminow and T. Li, pp438–513, Academic Press, 2002.

[10] S.S. Wagner, H. Kobrinski, T.J. Robe, H.L. Lemberg, and L.S. Smmot, "Experimental demonstration of a passive optical subscriber loop architecture," *Elect. Lett.*, vol.24, pp344–346, 1988.

[11] S.S. Wagner and H.L. Lemberg, "Technology and system issues for a WDM-based fiber loop architecture," *IEEE J. Lightwave Tech.*, vol.7, no.11, pp1759–1768, 1989.

[12] H. Shinohara, "Broadband access in Japan: rapidly growing FTTH market," *IEEE Commun. Mag.*, pp72–78, Sept. 2005.

[13] FSAN website: http://www.fsanweb.org/
[14] ITU-T, 1998, Recommendation G.983.1, *Broadband optical access systems based on Passive Optical Networks* (*PON*).
[15] ITU-T, 2000, Recommendation G.983.2, *ONT management and control interface specifications for ATM PON*.
[16] ITU-T, 2001, Recommendation G.983.3, *A broadband optical access system with increased service capability by wavelength allocation*.
[17] IEEE 802.3ah Ethernet for the First Mile website, available from http://www.ieee802.org/3/efm/
[18] ITU-T, 2003, Recommendation G.984.1, *Giagbit-capable Passive Optical Networks* (*G-PON*): *General characteristics*.
[19] ITU-T, 2003, Recommendation G.984.2, *Gigabit-capable Passive Optical Networks* (*G-PON*): *Physical Media Dependent* (*PMD*) *layer specification*.
[20] ITU-T, 2004, Recommendation G.984.3, *Gigabit-capable Passive Optical Networks* (*G-PON*): *Transmission convergence layer specification*.
[21] R.M. Metcalfe, "Ethernet: Distributed packet switching for local computer networks," *Communications of the ACM*, vol.19, no.9, pp395–404, July 1976.
[22] IEEE Standard 802.3, *Carrier sense multiple access with collision detection* (*CSMA/CD*) *access method and physical layer specifications*, 2005 Edition.
[23] IEEE Standard 802.1D, *Media access control* (*MAC) bridges*, 1993.
[24] Website of MEF: http://www.metroethernetforum.org/
[25] N. Frigo and C.F. Lam, "WDM overlay of APON with EPON—a carrier's perspective," available from http://grouper.ieee.org/groups/802/3/efm/public/sep01/lam_1_0901.pdf
[26] ISO/IEC 13818–1:2000, *Information technology—Generic coding of moving pictures and associated audio information: Systems*, 2000.
[27] K. Song and Yong-Kyung Lee, "Broadband access networks in and services in Korea," in *Broadband Optical Access Networks and Fiber-to-the-Home*, edited by C. Lin, pp69–106, John Wiley & Sons, 2006.
[28] J. Wang and Z. Zhao, "FTTH system, strategies, and deployment plans in China," in *Broadband Optical Access Networks and Fiber-to-the-Home*, edited by C. Lin, pp233–249, John Wiley & Sons, 2006.