CHAPTER 1

Introduction to First Mile Access Technologies

The Network Today

Since the deployment of ARPANET, networking has changed how we live our day-to-day lives. The tremendous reliance on networks as a method to enhance our quality of living has created a multibillion-dollar industry that has experienced near-exponential growth over almost three decades. From a conglomeration of semiconductor and telecommunication (telco) services to application-specific services such as optical and wireless networking, the telco industry has evolved dramatically over this time, adding newer products to the generic telco portfolio and emerging as a huge industry spread over large geographic areas and facilitating the transfer of both small and large amounts of information. This transfer of information between end users was propelled by the need to communicate over long distances and created the need for a telco infrastructure. This transfer of information also drove the information technology (IT) revolution.

The World Wide Web, based on the initial ideas of ARPANET, blossomed into a distributed architecture that allowed multiple users to communicate and created a parallel electronic economy. In both developed and developing countries, this growth led to the rapid deployment of network infrastructures. The emergence of data networking as opposed to voice transfer was a paradigm shift in network behavior and deployment in the 1990s. The significant surge in bandwidth—a result of data networking—created a requirement for high-speed core networks that were easy to install and that incorporated already existing fiber infrastructure and supporting network equipment.

Soon, nationwide backbones were built that could handle the transfer of several terabits of information in a few seconds. Two technologies that prompted the deployment of these high-speed core links were IP and wavelength-division multiplexing (WDM). IP emerged as the protocol of choice for data transfer traffic between hosts, evolving as a best-effort service that created a universally acceptable methodology. On the other hand, WDM showcased a way to maximize the usage of the near-infinite (30 terahertz [THz]) bandwidth fiber offered. With WDM, multiple wavelengths could be used to provide independent optical circuits (lightpaths), thereby alleviating the basic bandwidth bottleneck problem so evident because of the technology mismatch created from optical and electronic interfaces (optoelectronic bandwidth constraints). Another development that occurred for routing IP traffic over high-speed links was Multiprotocol Label Switching (MPLS), which served as a premier switching (Layer 2.5) technology that enabled the very fast gigabit-rate switching of IP packet trains at router interfaces.

On the end-user side, there was a massive increase in the use of personal computers, which enabled end users to create applications and compute software for personal applications at near-gigabit speeds.

These developments created a high-speed core and a high-speed end-user apparatus. However, this resulted in a void, often referred to as the *first mile access problem*, which emerged as a byproduct of the high-speed core and high-speed end computers; the high-speed core and high-speed end computers required the transfer of high-volume applications from the core to the end user and vice versa.

The first mile access problem can be summarized as the bottleneck created by the absence of technologies and solutions to accommodate the high capacity needs of core networks to reach end users. After all, end users want and need to access applications spread across network domains in real time and to access applications that require significant bandwidth. The development of bandwidth-killer applications, such as video on demand, e-learning, and so on, intensified the need for high-speed dedicated end-user connections.

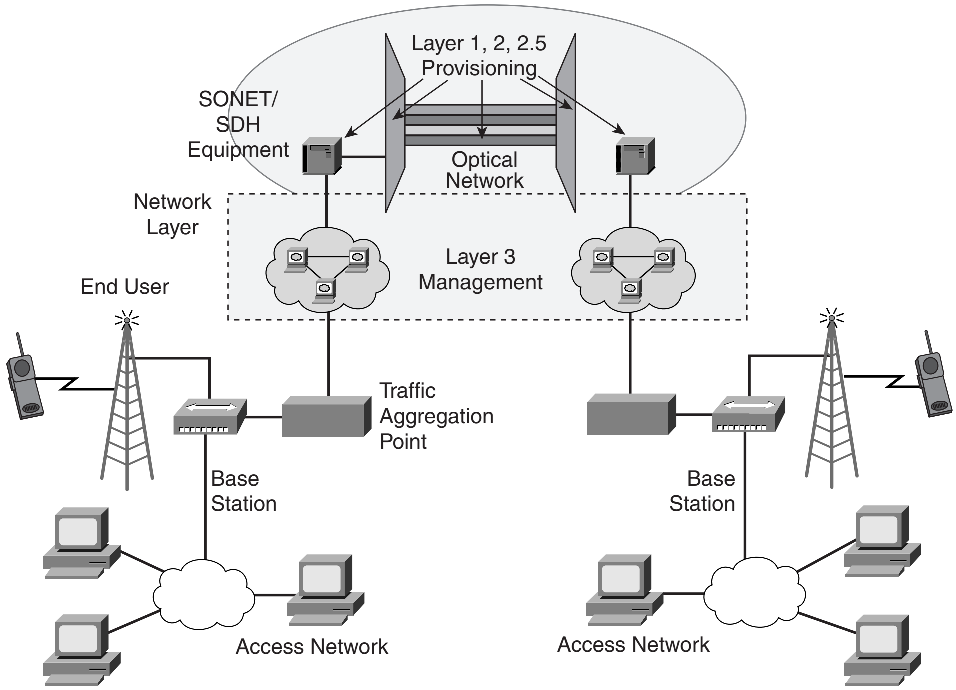
Despite the exponential growth in the number of Internet end users, serious concerns slowed investment in (and, therefore, technology maturation of) first mile products. One concern was end-user dynamic bandwidth requirements, or *bandwidth on demand*. Bandwidth on demand meant that needs would vary, and this uncertainty implied that there was not enough justification and motivation for investment in this area of networking. However, as bandwidth-critical applications became more and more prevalent, there surfaced once again a desperate need to solve the first mile access issue. An investment and technological plateau in the networking core segment shifted the investment focus to the first mile access area, enabling the development of technological solutions for first mile access problems.

Two approaches were proposed for first mile access solutions: wired networks and wireless networks. Wired networks, as the name implies, were created out of a wired infrastructure, and the material of the wire often dictated the bandwidth that could be provided to the end user. For example, a coaxial and copper solution provided no more than 8 to 10 Mbps of bandwidth to the end user. Power-line-based communication yielded 4 to 6 Mbps of line rates to the end user. Optical fiber-to-the-user (FTTU) yielded a wider bandwidth of about 100 to 1000 Mbps, creating an absolute abundance of bandwidth for the end user. In the wireless approach, wireless fidelity (WiFi) is gradually emerging as a standard for first mile applications, yielding a range of bandwidth availabilities depending on the WiFi quality and end-user distance from a wireless base station.

Bandwidth Management in Worldwide Networks: Impact on First Mile Access

Figure 1-1 describes a typical end user–to–end user scenario in which geographically dispersed users communicate with each other over multiple network segments. Typically we observe multiple users, both on wired and wireless access networks, connected to the network core. The sheer diversity of network protocols and user requirements gives rise to a bandwidth-management problem: the real-time challenge to provision networks to provide the pool of network users their multiple quality requirements.

Figure 1-1 *A Generic Network Showcasing Multiple-Tier Networks*



We can view the network as hierarchically layered based on core, metro, and access philosophies. The core network is often laid on fiber, such that the multichannel-based WDM system does transports raw bits through the high-speed connection. In this case, the bandwidth-management issue is to allocate wavelengths (upon demand) on a real-time basis and create these all-optical lightpaths between the source and destination. A migration from circuit-based lightpaths has yielded a more significant solution called *light-trails*, which is an optical burst solution using existing hardware and creating an out-of-band protocol that enables fast provisioning of the bandwidth to yield sublambda-level communication in the core. The absence of a protocol or framing procedure does not allow the legitimate marriage of IP directly over WDM—hence the need for a framing procedure. Synchronous Optical Network/Synchronous Digital Hierarchy (SONET/SDH) and Gigabit Ethernet are two conventional methods for transporting IP over WDM. Resilient packet rings (RPRs) are a more recent innovation to cater to bursty IP traffic transport over the optical layer. SONET/SDH has matured over the years and currently provides a synchronous transport mechanism in the core at speeds as high as 10 Gbps (OC-192/STM 64) and OC-768 or 40 Gbps under experimental setups. The drawback of such synchronous technology is the massive investment cost to cater to expensive high-speed electronics. Second, SONET/SDH or even RPR is not a very efficient protocol for IP-centric communication. At Layer 3, we have gigabit-capacity routers often working on a Layer 2.5 principle (that of MPLS), enabling high-speed switching of IP packet streams without the actual address resolution of the IP packets.

The significant influence of the enterprise segment of the industry has led to a surge in the need for metropolitan-area networks (MANs). Typically, metro rings, built on pure SONET/SDH or WDM technology, were built to cater to enterprise as well as aggregated access traffic. Metro networks have produced a steady and positive gradient in revenue, and hence there is strong justification for new technology and innovation (and investment) in this area.

As shown in Figure 1-1, the access area is a multitechnology zone. The primary bifurcation of technology yields wired and wireless segments, and it can be assumed that all end users are connected to the network using either of the two connection methods.

This book covers both wired and wireless ideologies, but delves deeper than just these approaches to focus on stronger and clearer philosophies such as passive optical networks (PONs), digital subscriber line (DSL), and power-line communication (among others). Before considering the individual technology stacks, we must look at the bigger picture—that is, how these various technologies work together, amalgamated, to provide a single network. It is at the bigger-picture level that the basic bandwidth-management problem emerges from the plethora of showcased access technologies.

The bandwidth-management problem can be defined as a network set up with a fixed number of resources (such as equipment and interfaces) and connected to a fixed number of end users whose demands vary over time. It is desired to provision services (bandwidth, quality of service [QoS], and so on) to these end users on a per-demand basis, maximizing the network use. This problem is a resource-provisioning problem and for most networks requires complex mathematical time computations (nondeterministic polynomial time complete, also called NP complete) for provisioning. In practice, the solution may be a best effort, or a pre-assigned scheme depending on the QoS a user desires at initialization. Such a solution may not be optimal but may be near optimal with the added time computation benefit. End-user bandwidth on demand also requires network resource management to ensure, in the most optimal way, the network functioning (including the network's capacity to deal with bandwidth flows through the network). The presence of multiple technologies in the same network creates a greater challenge involving the interoperability of these technologies at network peers. End users, whose requirements vary over time, also use multiple technologies, creating a potential management disaster—one that has multiple solutions at any given instant, with the optimum one being the hardest to find!

The First Mile Issue

The first mile problem can be thought of as an aspect of the phenomenon called the *digital divide*, which refers to an increasing gap between those who have access to useful online information and opportunities and those who do not. The expanded notion of digital divide holds that those who are underserved are at risk of more rapidly falling behind economically and in their quality of life to the extent they are unable to use IT effectively. This evolving notion of digital divide has come to refer to organizations and businesses as well as communities worldwide. One of the most optimal solutions to the digital divide is to provide broadband services to end users on a massive worldwide scale.

The term *broadband* is referred to under the Telecommunications Act of 1996 as advanced services (that is, data transmission rates) significantly higher than those that can be sent through ordinary high-quality voice circuits (that is, more than 56 kbps). The industry definition of broadband services is the capability to provide end users (consumers as opposed to customers) a dedicated connection greater than 200 kbps.

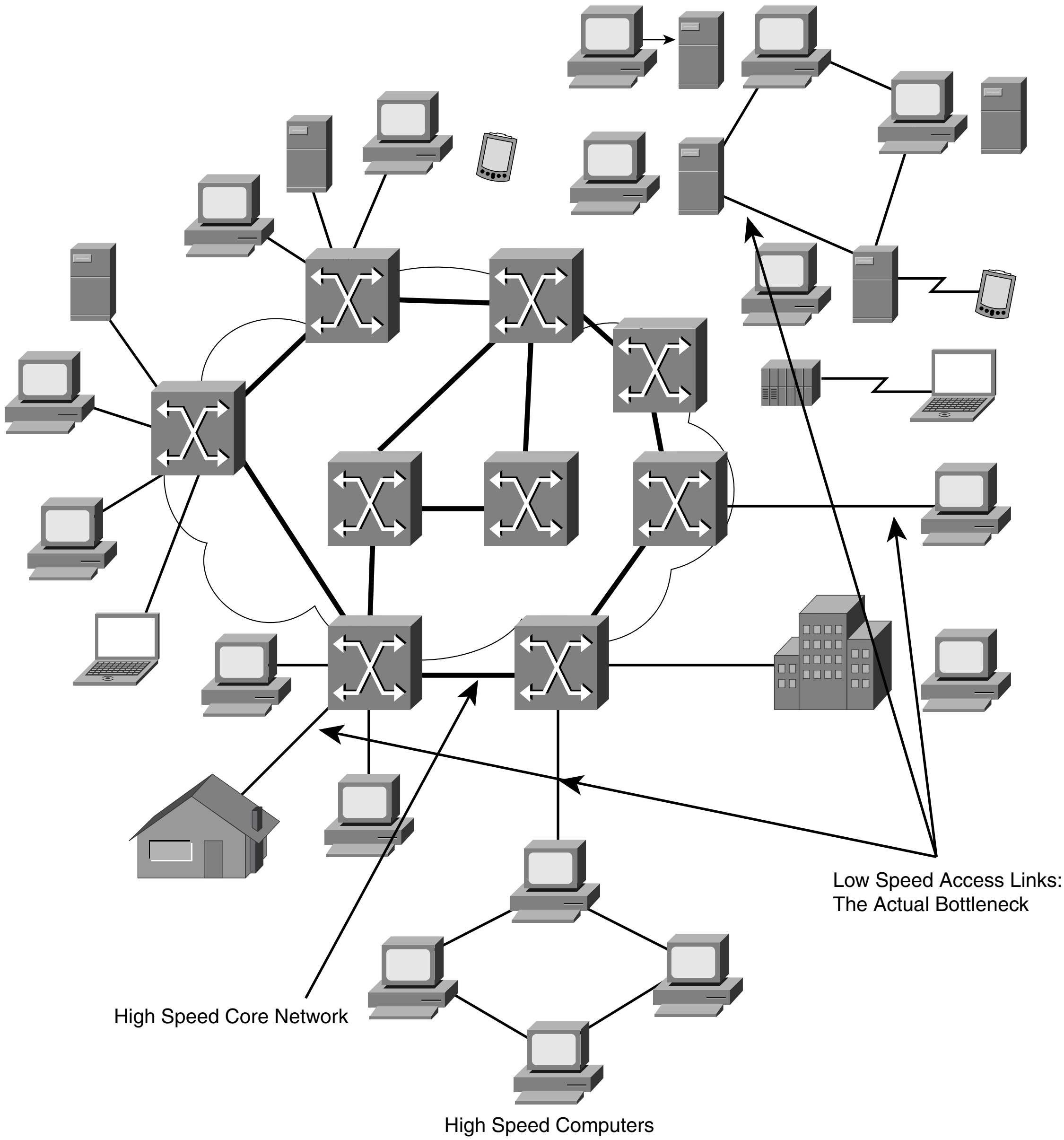
Business Justification for the First Mile Problem

Technically, and as explained previously, the first mile access problem concerns providing high-speed access to end users. Two rapid developments caused the first mile problem:

- High-speed desktops
- High-speed network cores

The products and services in these industry segments have expanded (and matured) significantly, driven by developments in the telco and computer industries. Gigahertz-rate-capable computers have become an easily obtained commodity and are increasingly seen on the desks of end users. The rapid surge in Internet traffic led to service providers and carriers buying and installing in the core of networks high-speed (Gbps rate) equipment manufactured by vendors, such as Cisco, Nortel, and so on. The Internet soon became a high-speed backbone, a network of networks, capable of gigabit-rate throughputs on high-speed connections (typically on optical media). This resulted in a bottleneck between the high-speed network core and high-speed computers sitting on the desks of the end users. Figure 1-2 shows a schematic of the current situation. We can observe that between the high-speed core and high-speed desktops exists the access networks, which are typically low-cost, low-speed access links often on coaxial cable and copper that cannot support data transfers of more than a few megabits per second.

Figure 1-2 *Access Bottleneck*



This tremendous growth in information transfer rates (both network core and end-user transfers) created what is today commonly referred to as the first mile access problem. Although it was necessary (and desirable) to upgrade technology at both the ends (core and user), the IT industry, often hampered by regulatory laws, failed to upgrade the technologies that carried data to end users.

In addition, because investments in coaxial cable and shielded twisted pair (STP; phone lines) to facilitate data transfers were so high initially, telcos did not to invest to rejuvenate this area. STP emerged as a technology (and solution) that was far more resilient and useful than for just the transport of plain voice signals (at 64 kbps). By using the same spectrum either completely, as in dial-up access, or in shared-spectrum format (coexistence of the two signals), as in DSL, data transport could be clubbed on to the same STP wire. By using a modulation technique, a baseband data signal could be modulated to provide a high-frequency signal that was transmitted over the STP medium. Modulation here meant the variation of a high-speed carrier with the baseband signal to produce a modulated high-frequency (frequency modulation) or variable-amplitude (amplitude modulation) or phase-shifted (phase modulation) waveform. Devices that can modulate and demodulate the baseband signals are called *modems*, and modem modulation speeds were critical in determining the data rate that could be extracted from STP media. Therefore, access networks typically relied on STP as the medium by which to provide a reasonable data flow to end computers. Of course, the data flow provided even after maturation of technology was typically less than 56 Kbps in direct modulation and about 1.5 Mbps using variants of DSL.

In no way was this data rate comparable to the speeds obtained by the two ends of the network, namely the high-speed core and the super-fast personal computers. As mentioned previously, this speed discrepancy highlighted the basic access bottleneck problem faced today. However, carriers and providers could still justify their lack of investment in the access area. First, as explained earlier, STP was a very efficient medium for data transfer. Initial Internet applications were restricted to e-mail and simple web use. Second, the amount of existing infrastructure and the investments already made for STP-based Public Switched Telephone Networks (PSTNs) were very large. Most developed countries took six to seven decades to lay this massive PSTN infrastructure, but this perseverance resulted in an excellent medium to reach end users and homes. Because they had a high telephone density, developed countries were able to absorb data traffic seamlessly in their PSTNs.

However, as web-based applications grew from plain e-mail and browser applications to more attractive multimedia and video applications, the need for bandwidth to the end users increased phenomenally. Supporting such high-bandwidth killer applications required an upgrade to these large and cumbersome (geographically diverse) telephone networks. However, it was observed that the need to provide high bandwidth to end users did not justify the level of investment required to upgrade these networks. Other factors also slowed the development of the PSTN from a voice-only network to a broadband network. Among others, the dot-com bubble and the shattering of the telco industry created a negative environment for investment in this sector. However, a slowdown in core networks in terms of capital spending and the failure of the basic telco business model have once again rejuvenated interest and investment in the first mile access area.

Technological Aspirations Forecast for First Mile Access Networks

The dearth of revenue in the core of worldwide networks, and the absence of a business model that alleviated the debt traps of the telco industry, created a plethora of reasons for wise investments in the first mile access area. The most logical implementation of the first mile access area networks was the direct adaptation of MANs. However, MANs are typically characterized by their superlative performance and stringent behavior patterns expected (and are thus costly). Leading companies and groups the world over conducted research in this area and defined a direct need for technology that could solve the first mile access issue (that is, provide connectivity to the end user). The absolute identification of the first mile issue hastened the process of developing newer access area technologies.

Networks continued to adapt MANs to deal with first mile access issues, and a business case could be made in their favor. Despite this, however, a positive response met the efforts of the research community to streamline access network technology.

Broadly, two well-defined strata of access network technologies can be identified: wired technologies and wireless technologies. Conventional networking fomented and supported the belief in wired networks (over different media and using different protocols). Wired networks were conventional, low cost, and functioned on an infrastructure that generally already partially existed (or in whole in some cases). The main objective was to provide somewhat basic connectivity to the end user. Wire technologies included, among others, DSL and its variants, cable technology, PONs, and basic dial-up services. On the other hand, the past two decades justified a strong investment and deployment scenario in wireless networking. From basic wireless telephony evolved a requirement to transfer wireless data to end users. The idea of having connectivity to end users, through a wireless medium, also justified the revolution in portable devices such as laptops and handheld computers. This created a parallel access technology in the wireless medium.

In the following sections we discuss each of these technologies to show the basic capability of each incumbent to provide the necessary bandwidth to end users and consumers.

Technologies Deployed in Access Networks

As mentioned before, two main technological classifications can be seen in access telco networks: wired and wireless technologies.

Wired networks generally mean a physical connection to the end user, whereas *wireless* networks mean an absence of such a physical connection. At the time of this writing, the technological classifications of wired networks are as follows:

- DSL
- Coaxial cable
- Fiber (PON and coarse WDM [CWDM])
- Copper (for example, Ethernet)
- Power-line communication

In the wireless domain, the following three technological innovations were seen as key attributes to access networking:

- WiFi
- Basic cellular technology
- Infrared and free space optic communication

DSL Technology

In its most primitive form, DSL technology can be considered as the coalescing of data and voice on the same PSTN. By using the medium (STP) as a band-pass filter and by multiplexing (in this case, sharing) the voice and data formats on individual slots (bands), we can optimize the use of the STP in the access. Further variants of DSL technology are asymmetric DSL (ADSL), very-high-data-rate DSL (VDSL), and high-data-rate DSL (HDSL), each of which is explained in Chapter 7, "DSL Technologies." The high-bandwidth core networks can feed data to the access networks. The end users segregate the voice from the data by using a low-pass (voice) and a high-pass (data) filter. By virtue of its physical property, copper does not allow for high-bandwidth communication. Moreover, copper wire also has a high attenuation. Therefore, the signal at high frequencies (data) cannot travel large distances, a severe drawback for DSL technologies. A DSL modem, typically a filter, can segregate the voice and data from the band-pass channel. Further coding of the data waveform by a keying or coding technique, such as Quadrature Phase Shift Keying (QPSK), can create and allow transmission of higher-bit-rate signals.

Because of its dependence on copper as a medium for communication, DSL is restricted in data rate and distance. In addition, it is not easy to increase the distance of DSL transmission by installing repeaters. A DSL repeater needs to extract the signal and then process it, and hence this cannot be accomplished technologically and does not justify the costs involved. This limits DSL transmission to the last mile, and further limits it to small distances on account of the high attenuation of the signal traversing a copper channel.

Another issue with DSL and its family of transmission technologies is the directional power of communication. Typically it is desired that a technology be able to provide a seamless communication flow, from the core network to the end user (and vice versa). This kind of transmission is called *bidirectional* or, in telco language, *full duplex*. The bit rate achieved from the end user to the core should be the same as the bit rate achieved from the core to the end user. However, Internet traffic analysis generally reveals that the amount of data in upstream communication (from the end user to the core) is much less than the amount of data that flows from the core to the end user, by a typical ratio of 2:7 to 2:9. Hence DSL, to surmount some of its technical disadvantages, offers a symmetric and an asymmetric version.

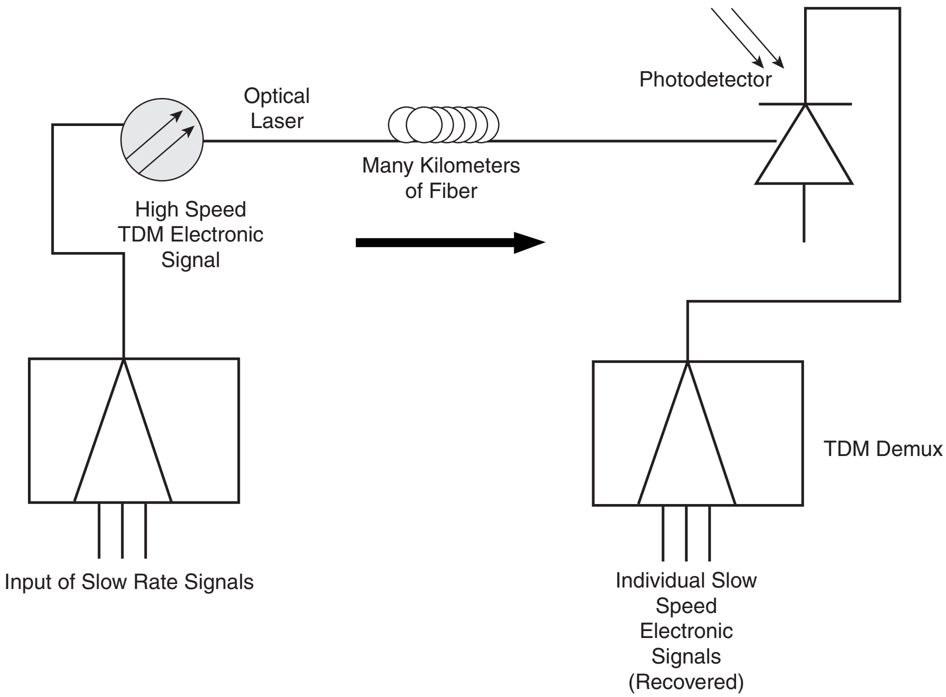
In the symmetric version, the data rate from the end user to the core is the same as the data rate achieved from the core network to the end user. In the asymmetric version, the data rate available from the core to the end user is different (typically more) than the data rate available from the end user to the core. This creates a system that is optimized for normal operation of IP traffic. However, this creates severe buffering issues when there is reverse transfer of data (typically uploading or sending large files). In short, the asymmetric system works well for normal operations such as web surfing or even downloading multimedia, but there can be severe delay penalties in reverse operations such as uploading files or sending multimedia contents (and, especially, when using bandwidth-intensive applications such as videoconferencing).

Fiber

Optical fiber can be considered the biggest breakthrough (along with wireless) in communication technology of the past century. Possessing a bandwidth of 25,000 GHz, a single strand of optical fiber is as thin as a human hair. Glass as a medium for communication was proposed in the early 1960s, but it was not until recent innovations in laser, detector, and optical amplifier technology that fibers were used for commercial communication.

Different methods of communication have evolved for fiber as a medium of transport. Initially, a time-division multiplexed (TDM) electronic signal (at lower speeds on to a high-speed TDM signal) was modulated by a laser diode and fed (coupled) to a fiber. These optical signals were detected at the far end, across a large distance, by a photo detector. The converted electronic signal was further demultiplexed in the time domain to get individual slower signals at lower bit rates. Figure 1-3 shows a schematic.

Figure 1-3 *Optical Transmission System*



Fiber communication can be classified further based on the physical characteristic of the optics involved. Typically, the laser, which injects the optical signal, emits light at a closely knit group of wavelengths. A laser that emits its optical power in a narrow stream such that most of the optical power is concentrated around one wavelength is called a *narrow-aperture laser*. Such a laser is also said to possess negligible chirp, and according to classical physics the emitted light travels in a fiber that supports this wavelength. Although negligible, the attenuation of an optical signal in a fiber is still finite, and this signal depends on the wavelength it is traveling on. In other words, the attenuation in a fiber is wavelength sensitive.

Finally, in the early 1990s a scheme developed to maximize the use of the near-infinite capacity of fiber. This scheme, called *wavelength-division multiplexing* (WDM), is a method to pack multiple signals (each on different wavelengths) in the same fiber by the spatial diversity of the wavelengths. The main motivation for the development of this scheme was the optoelectronic bottleneck—that is, the inability of electronic systems to modulate more than 10 Gbps of data even though fiber could allow up to 25,000 Gbps of data. This discrepancy was in some way alleviated by WDM solutions. Although WDM is a typical metro and core solution, some aspects are applied even to the access area. This low-cost, easy adaptation of the WDM solution in access is called *coarse WDM* (CWDM) (in contrast to dense WDM [DWDM] in the core).

Attenuation Windows in a Fiber

Authors have always argued about the number of operating windows of wavelengths or bands that can exist in an optical communication network. To the designer or systems engineer, this is not much of an issue for argument, because practical optical networks currently function in three discrete bands: the conventional (C), long (L), and short (S) bands.

The C band is approximated from 1525 to about 1565 nanometer (nm). It has a low loss of about 0.2 decibels per kilometer (dB/km). C stands for *conventional* and most metropolitan as well as long-haul networks use this band. The band is about 40 nm and can accommodate 80 different wavelengths, each 100 GHz (or 0.8 nm) apart. The spacing between the wavelengths is a standardized value. Currently, for dense-division multiplexing, the spacing is standardized at 0.8 nm or 0.4 nm.

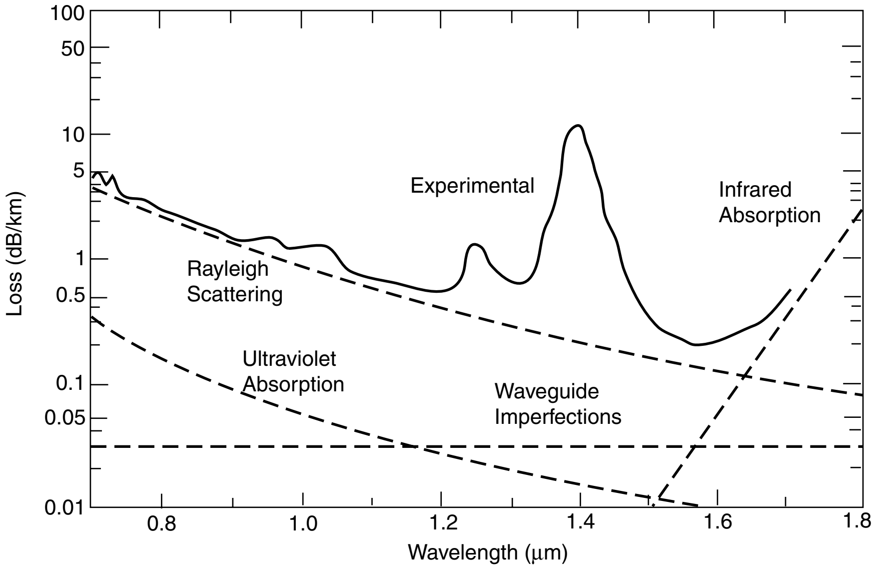
The L or long band starts from about 1570 nm and extends to 1620 nm. It has slightly higher loss than the C band but has similar characteristics to the C band. Much research has been carried out in this band and signs of early commercial deployment are evident. The future could see a lot of vendors positioning their DWDM products and technologies in this band.

The S or short band is spread around the 1310-nm window. It is of strategic importance due to its close proximity to the zero-dispersion wavelength (a wavelength around 1300 nm that has minimal dispersive effects due to the cancellation of material and wave guide dispersions by each other). It has a higher loss than the C band at about 0.5 dB/km and hence is not the best solution to long-haul communications. The evolution of wider technologies for the C band, such as doped amplifiers, switch matrices, and filters, makes the S band rather underused.

Apart from these three standard bands, there is also the traditional 850-nm band, which was first used for optical communication systems. The 850 to 980-nm band is mostly used for multimode systems and for short LANs. It has a high loss characteristic of almost 2 to 3 db/km. Experimental research is focusing on the 1400-nm segment for new methods to eradicate the OH^- (hydroxyl) molecule. The best a design engineer can hope for is to have a continuous band from 1300 nm to 1650 nm yielding about 400 wavelengths 0.8 nm apart and 800 wavelengths 0.4 nm apart.

Figure 1-4 shows the attenuation curve in a fiber.

Figure 1-4 *Attenuation Curve in a Fiber (Reprinted from* IEEE Electronics Letters, *1979)*



Passive Optical Networks

Passive optical networks are a technological innovation that can alleviate the first mile bottleneck issue in access networks. As the name implies, passive optical networks are typically *passive*, in the sense that they do not have active components for data transport. They may be spread across different physical topologies. PON development, although propelled by the surge in bandwidth requirements, also answers a definite need for low-cost optical networks for end-user applications. During the initial phase of PON development, some of the primary desirable features of a PON were as follows:

- **Low-cost network, low-cost components**—Because the revenue was in the number of consumers (quantity) rather than the pure service delivery to each consumer (quality), the amount of investment each end user would have to make had to be kept to a bare minimum. In metro and core networks, at each network element a composite WDM signal could drop an entire wavelength or a group of wavelengths. In contrast, in the access first mile area, each network element at the consumer site had bit rates typically of the order of 100 Mbps or even less.

- **Ease of management**—The first feature of low cost also initiates the second point of management complexity. Management complexity creates undue surges in network equipment cost. What is desired is a simple, efficient, and scalable management system that can manage the network and guarantee the network users of some network parameters such as QoS, delay, fairness, throughput (service level agreement [SLA]), and resiliency.
- **Upgradability, in-service upgrade, and interoperability**—The rapid development of newer technologies creates a need for ease of upgradability in PONs. In soft upgrades, the basic fabric remains the same, but a software upgrade enhances the features of the network. Because most of the end users are residential customers or enterprise users, in-service upgrades are important so as not to disrupt real-time services in PONs. Finally, due to the high-volume nature of PON users, there is a strong probability of PON networks having multivendor equipment in them. To facilitate ease of communication and create fair-competition interoperability, standards must exist for PON network elements to talk to one another.
- **Guarantee of basic network features**—The PON must be able to guarantee the end users some degree of network parameters, which are promised at inception (SLA). Although low-cost networks and simple protocols are generally designed for best-effort service, the quantum leap from traditional broadband to PON represents a sea-change shift in the end-user paradigm, and end users must get the desired services through the PON to justify the cost of deployment.
- **Security**—A PON topology is typically that of a star; hence, all the nodes in a star have access to the broadcast information sent by the hub. It's imperative to secure the information by secure services and methodologies such as 802.1x and MAC layer encryption along with virtual private network (VPN) services.

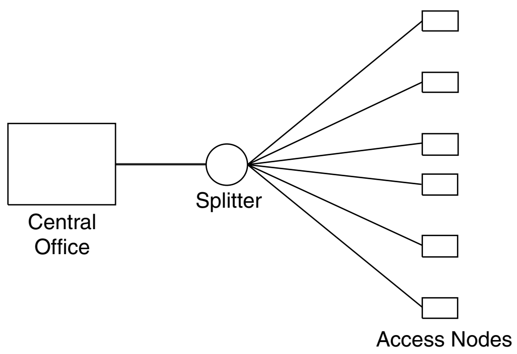
Under current implementations, the following three kinds of PONs exist:

- **ATM PON (APON) and Broadband PON (BPON)**—These types of PONs support extra overlay capabilities for high-speed delivery. APON is the PON transmission technique based on the ATM signaling layer; it was developed by five service providers as part of the Full Service Access Network (FSAN). BPON is approved as International Telecommunication Union (ITU) spec G.983x. It supports data rates to 622 Mbps out to an endpoint (upstream) and back from the customer to the service provider's remote aggregation point (downstream). (Courtesy Lightreading.com.)
- **Gigabit PON (GPON)**—This PON type can support up to 2.5 Gbps of traffic and uses Generic Framing Protocol (GFP), which is SONET compatible, so it allows the creation of an end-to-end unified system based on TDM hierarchy. At this time, GPON is not standardized but is under the umbrella labeled G.984.x.

- **Ethernet over PON (EPON)**—This type is the simplest type of PON, consisting of broadcasting Ethernet frames in the star. It requires a multipoint-to-single-point protocol to guarantee collision-free communication in the upstream because of its shared nature.

In the simplest architecture, a PON network is a star connection. At the core network side, there is an optical line terminal unit (OLTU, or OLT for short), whereas the end-user side has an optical network unit (ONU). Multiple ONUs are connected to a single OLT in a star configuration. This creates a broadcast medium by virtue of the fact that a single optical splitter splits the optical power from the OLT to each of the ONUs. Different mechanisms, such as ATM, Ethernet, and so on, guarantee a good throughput to each ONU (that is, a guarantee of a good share of the total bandwidth to each ONU). In Chapter 2, "Passive Optical Networks in the First Mile," we cover each of these mechanisms in detail and examine the solutions from a technology point of view. Figure 1-5 shows a basic PON configuration where the central office is the OLTU and access nodes are ONUs.

Figure 1-5 *Basic PON Configuration*

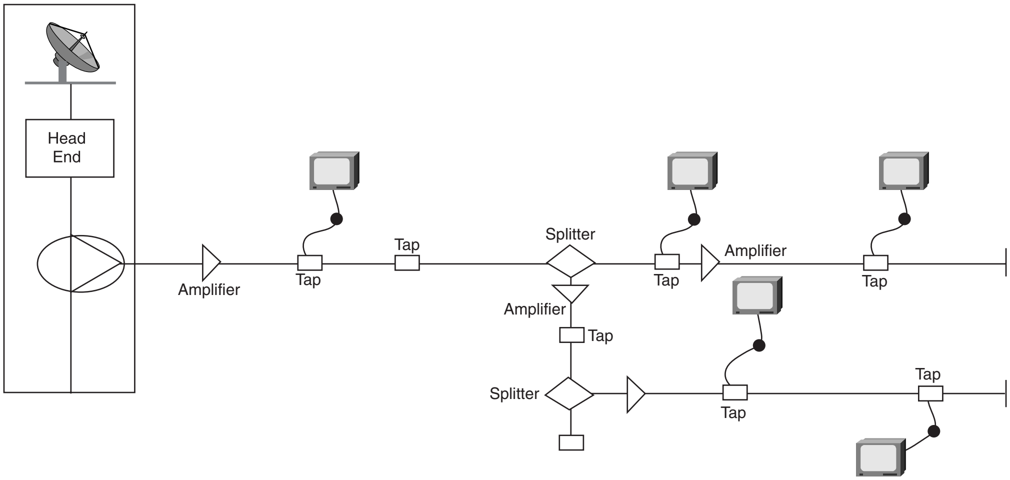


Cable Networks

Community Antenna Television (CATV), commonly known as cable TV, was invented to solve the issue of poor TV reception in rural areas. Ever since, CATV rose above its challenge and today almost 95 percent of U.S. communities have access to CATV networks. A typical CATV distribution network is comprised of coax cable, headend systems, and customer end devices. Frequency-division multiplexing (FDM) is used to transport programs or data over the hybrid coax cable. CATV usually makes use of the 50 to 550 frequency spectrum, with each channel spreading over 6 MHz of the frequency band.

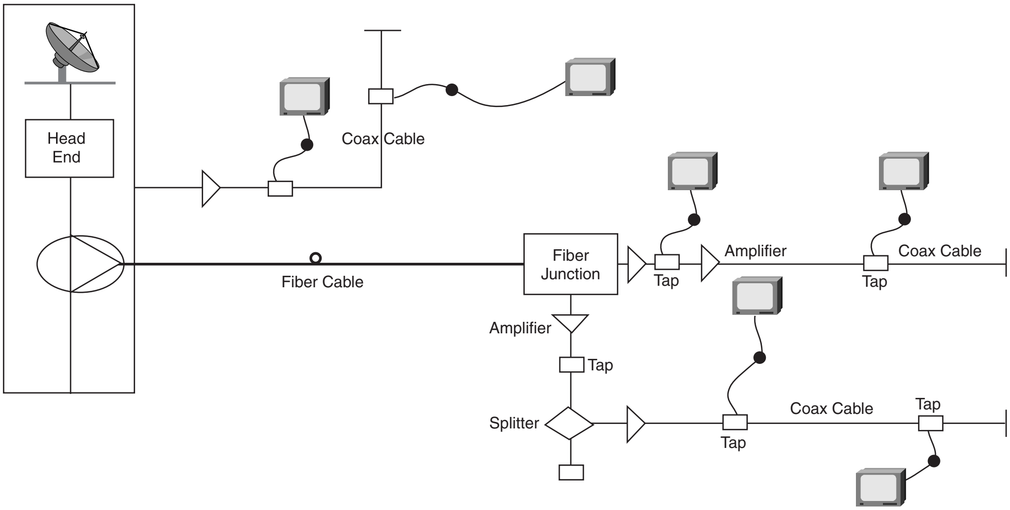
At the headend (collection point), programs received from satellite or microwave systems are converted to one of the preset channels, Then the channels are scrambled (coded) according to the desired quality (paid or free) and multiplexed onto a single broadband analog spectrum or band (by FDM) before being broadcast to the CATV subscribers. The headend along with coaxial cables and subscribers (set boxes) comprise a typical cable system. Subscribers are connected to the feeders or trunk with a drop cable and tap (connector). Figure 1-6 shows the architecture of a one-way cable system. The signal strength attenuates by the square of frequency as the signal propagates through the cable. To maintain signal strength, amplifiers are installed every 1 kilometer or so.

Figure 1-6 *A Simple Coax CATV Network*



Pure coax systems are incapable of driving high-speed residential broadband services. Coax systems can only provide up to 40 channels, which puts the CATV system in direct disadvantage when competing against direct-broadcast satellite systems. Coax cable systems lack robustness and are very difficult to design and maintain. The limitations of amplifiers (capacity) and of the maximum distance the signal can travel without degradation are also restraining factors to providing scalable broadband services. To overcome these issues that relate to the inherited coax systems, cable operators proposed to use fiber as a trunk medium. The total system is comprised of both fiber and coaxial cables, hence the term *hybrid fiber coax (HFC) networks*. Figure 1-7 shows a typical HFC plant. Between the subscriber and the fiber node (junction), the assembly of coaxial cables, amplifiers, splitters, and taps is same as the pure coaxial cable networks.

Figure 1-7 *Hybrid Fiber Coax Cable (HFC) Network*

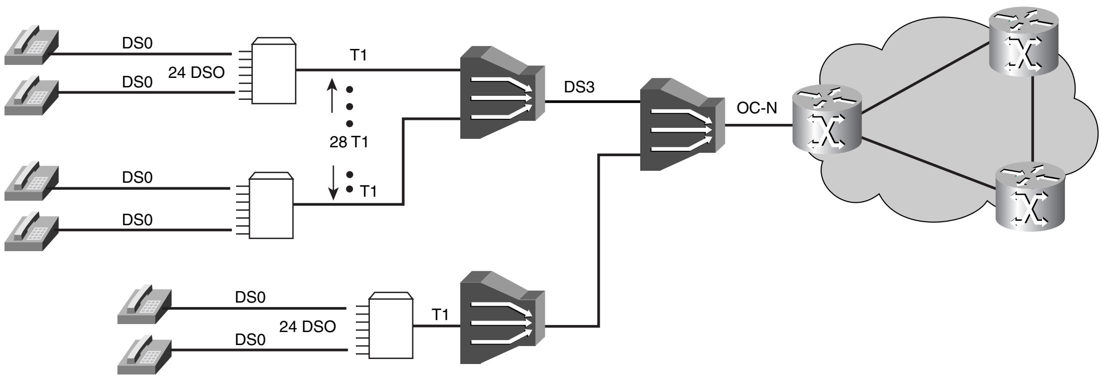


Today, most cable revenue comes from content delivery. The extended service offering using IP-enabled signals delivered over standards-based infrastructure (Data Over Cable Service Interface Specifications [DOCSIS]) helps service providers explore new revenue opportunities.

The PSTN

The Public Switched Telephone Network (PSTN) forms the backbone of most of today's wired voice communication. Figure 1-8 shows a generic PSTN.

Figure 1-8 *PSTN: From Phones to the Voice Routers*



The PSTN started as human-operated analog circuit-switching systems (typical form of plugboards) and progressed through electromechanical switches. By now this has almost completely been made digital, except for the final connection to the subscriber (the "last mile"): The signal coming out of the phone set is analog. It is usually transmitted over STP as an analog signal. At the telco office, this analog signal is usually digitized, using 8000 samples per second and 8 bits per sample, yielding a 64-kbps data stream (DS0). Several such data streams are usually combined into a fatter stream: In the U.S., 24 channels are combined into a T1; in Europe, 31 DS0 channels are combined into an E1 line. This can later be further combined into larger pipes for transmission over high-bandwidth core trunks. At the receiving end, the channels are separated, and then the digital signals are converted back to analog and delivered to the receiver phone.

Although all these conversions are inaudible when voice is transmitted over the phone lines, they can make digital communication difficult.

In other words, the PSTN offers the end user a fair amount of connectivity, both in terms of voice and data. Before the advent of fiber, as a communication medium, the STP along with coaxial cable were the sole wired media that could be used in modern networks.

Wireless Networks

The idea of being able to access information while not compromising on mobility gave tremendous impetus to wireless networking. Users were and are fascinated by the idea of being able to communicate without being connected to the backbone network through a wire. This led to the development and successive deployment of wireless and cellular networks. Initially, wireless networking was relegated and confined to voice communication. The initial idea was to provide the public with wireless telephony, and its use was restricted to emergencies and short calls. Later, wireless telephony became a strong topic of research, and the opening of new frequency spectrums created two parallel spheres of business. Broadband wireless offered in 2.4-, 5.5-, and 11-GHz bands for data and voice coalesced. Cellular technology developed wideband code-division multiple access (WCDMA), global system for mobile communication (GSM), and so on for voice communication. Wireless technology to the last mile was a new approach floated recently by multiple vendors and part of the recently standardized IEEE docket 802.11b. At high frequencies such as 2.4 GHz and 5.5 GHz, large spectrums of frequencies could provide end users the necessary data rates for first mile applications. Three main areas of technological development sustain wireless broadband networking:

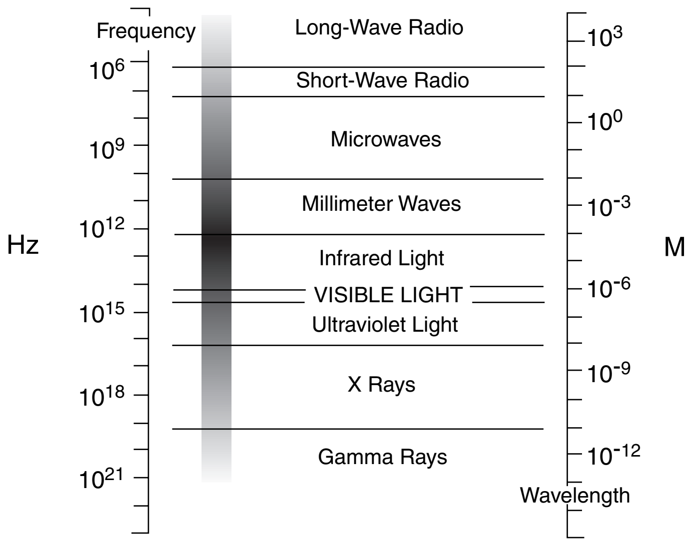
- Fixed wireless
- WiFi
- Infrared and free space optics

Fixed Wireless

Where a wire could not be placed, or where there was a need for a high QoS data rate, fixed wireless was deployed. Fixed wireless technology typically is based on microwave communication. Two microwave antennas (both geographically fixed) are located at some distance from each other. The microwave signal is created by a cavity method (for example, klystron cavity) and fed through the antenna, which broadcasts the same. The receiving antenna in the line of sight receives the signal and may act as a repeater for increasing the distance. Microwave communication is restricted to communication of signals whose wavelengths (λ) are in the micrometer range. Therefore, although large volumes of data can be transmitted on such waves, they are severely limited in transmission distance on account of the attenuation they experience. The typical application of microwave communication is to link two base stations or cell sites to each other. From the first mile access point of view, however, microwave communication can considered an excellent choice for reaching end users without the need to lay high-bandwidth wire, which in this case is fiber. Of course, the penalties are the distance the signal can travel, the maximum bandwidth available, and the line-of-sight limitations in microwave communication.

Figure 1-9 shows the wireless spectrum.

Figure 1-9 *Figure 1-9 Wireless Spectrum*



WiFi: Wireless Fidelity

The standardization of the 802.11b format for wireless networking has paved the way for tremendous research and deployment efforts for WiFi networks. A WiFi, in short, is a high-performance high-bandwidth network built on the wireless LAN (WLAN) concept. A wireless transmitter at one of the Industrial, Scientific, and Medical (ISM) frequencies (2.4, 5.5, and 11 GHz) emits a signal that can be received by a small wireless receiver. The high bandwidth and ease of communication renders WiFi a good choice for last mile wireless networks. Multiple vendors have demonstrated new products that are 802.11b compliant and are able to provide networks with high QoS to the end user. Further details are provided in Chapter 4, "Data Wireless Communication."

Infrared and Free Space Optics

Because the wireless spectrum seemed to be too small for data traffic, and there seemed to be a bottleneck between the data that emerged from a fiber and that which could be fed into a wireless channel, there was a new development effort to use other parts of the electromagnetic spectrum. Two such efforts were infrared and free space optics. Principally similar to each other, both techniques include the modulation of data waves onto an electromagnetic wave (light or infrared) and achieving phenomenal bit rates.

In free space optics, the motivation is to use the several thousand gigahertz of available bandwidth at those high (THz) frequencies. Free space optics means point-to-point communication and is further limited by line of site. Typically, a laser diode sends an optical signal through free space. This signal travels through air (undergoing attenuation, fading, and so on) and reaches the receiver. A portion of the transmitted power is received by the receiver. The receiver then detects the signal and communication is achieved. There is high loss in such a system, but the bandwidths achieved are quite high.

When distances are small, instead of free space optics it is more convenient to use infrared waves. Infrared frequencies are much easier and cheaper to generate and are generally able to give a good throughput (bandwidth). Typical applications include portable digital assistants (PDAs) and handhelds within a room.

Comparison of First Mile Access Technologies

Table 1-1 compares some of the technologies deployed in access networks that are covered in this chapter. In this chapter we have covered multiple technologies and have discussed each technology in some detail. The forthcoming chapters highlight each technology and showcase circumstances when the appropriate technology can be used.

Table 1-1 *Comparison of First Mile Access Technologies*

Service	Medium	Intrinsic Bandwidth	Per-User Bandwidth	Standard	Issued By
DSL	24-gauge twisted wire	10 kHz	8 Mbps	G.992	ITU
Cable modems	Coax (HFC)	1 GHz	10 Mbps	DOCSIS 1.1	Cabelabs
APON BPON (ATM)	Fiber	25,000 GHz	10-1000 Mbps	G.983 FSAN	ITU
EPON (Ethernet)	Fiber	25,000 GHz	10-1000 Mbps	EFM	IEEE
WiFi	Wireless	2-4 GHz	1-5 Mbps at distance	802.11b	IEEE
GPON	Fiber	25,000 GHz	Up to 100 Mbps	ITU G. 984	ITU

Summary

This chapter showcased multiple technologies and solutions that can be used for first mile access. We have in this chapter defined the basic problem faced in first mile networks and explained the need for multiple solutions in this area. Based on this diversity of needs and applications, there is a generic evolution rather than revolution of new technologies from core and LANs that solve the first mile access area problem. First mile access networks are thus an eloquent solution to solve the future business needs of telco networks.

We have, in this chapter, briefly discussed the multiple technologies that underline first mile advanced access networks. Among others, we covered PON, fiber (CWDM), DSL, wireless, and PSTN as discrete contenders for first mile solutions. In the following chapters, we deal with each of these technologies and design first mile access networks, to fill the void created by the emergence of high-speed core and high-speed PCs.

Review Questions

1. Define first mile networks.
2. What are the key enabling technologies in first mile networks?
3. What are the business justifications for first mile networks?
4. What are the applications in first mile networks?
5. How would you differentiate technologically in a first mile network?

6 What are the two primary reasons for the massive growth of first mile networks?

7 Define broadband and explain how broadband can solve the digital divide.

8 Compare GPON, EPON, and BPON from technological and standardization perspectives. What are the key reasons for each development?

9 How do multiple technologies work over a PSTN?

10 From Table 1-1, differentiate each technology solution in terms of services. For example, for pure voice lines a PSTN is sufficient, but for videoconferencing we need higher speeds (and hence ADSL is required). List all the possible applications that a technology can provide.

11 Based on Question 10, list all the salient applications that a particular technology can provide that no other technology can provide.

12 Define bandwidth management. How is it related to bandwidth on demand? Considering that there *n* users in a network (where *n* is sufficiently large) and there are *k* service types that a user can subscribe to, prove that allotting bandwidth in real time is not possible in this network without a heuristic well-defined algorithmic solution. Hint: Show that the solution that does not have any standard algorithm is NP complete.

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