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5 Cable Modem and HFC

Albert Azzam

CONTENTS

5.1 OVERVIEW

Developing a high performance National Information Infrastructure (NII) for the information age is a national goal. For the United States, one of the major objectives of the *Telecommunication Act of 1996* is to promote a competitive environment in which old and new communications providers build a network of interconnected networks. This new infrastructure should support new interactive multimedia services that are becoming popular with a phenomenal growth on a widespread basis.

In this chapter, the cable modem is described. Making the cable modem functional will require costly modernization efforts of the cable network so it can communicate bidirectionally. To fully describe the technology of the cable modem, its environment is briefly described so the reader has a better appreciation of the various assumptions made to develop this technology.

This chapter is organized in two parts:

1. the cable network environment in which the cable modem must operate
2. the two cable modems the industry is specifying mainly:

   - ATM-centric cable modem
   - IP-centric cable modem

5.2 MARKET PULL/TECHNOLOGY PUSH

Today's networks, worldwide, are service specific. Cable TV networks were optimized for video broadcasting (one way). Telephone networks, including wireless, were deployed specifically to handle voice traffic. Both platform and fabric were optimized in the design to switch voice traffic efficiently. The Internet was initially developed and optimized for data transport. None of these service specific networks can cope or was designed to provide these emerging interactive services.

In 1993, the Internet emerged not just as a way to send e-mail or download an occasional file but as a place to visit, full of people and ideas. It became *cyberspace*. Its impact quickly spread as everyone wanted to experience this virtual community. The Internet frenzy is a worldwide phenomenon. Europe, Asia, and developing countries are building the Internet infrastructure at a faster pace than the telephone companies and creating a new market for high speed Internet connectivity. The high demand market for digital data, voice, image, and video transmission necessitates the latest and greatest access technologies. Moreover, today's users are becoming knowledgable about the performance that network services must provide if their bandwidth hungry applications are to work adequately. Advanced Internet and broadband applications are being developed in various research centers, including government agencies through Next Generation Internet funding (NGI), Internet 2 Consortium, and universities all over the globe.

Service specific optimization is most prevalent in the local access networks where deployment and operating costs are directly associated with individual customers. The AT&T and TCI merger is a case in point. Hence, the value of a communications network increases with the number of locations it serves and the number of individual users. The two emerging high speed interface technologies are ADSL and cable modem.

The information age has penetrated our society at all levels: education, business, government, marketing, entertainment, and global competition. All these factors are clear to the long term planners for both the telephone and cable operators. The business reality, however, may take precedence over long term strategies, and as always the free market will determine the outcome.

To meet this business model, the cable multiple system operator (MSO) developed the high speed cable modem as the technology of choice. The telephone companies, on the other hand, opted to provide high speed access via ADSL over copper lines.

5.3 CABLE NETWORK AND EVOLUTION TO HFC

5.3.1 History of the Cable Network

The cable network was originally deployed to perform a very simple task. Reception of TV signals was very poor, especially in suburban areas where the middle class began moving in the sixties. This CATV network used coax shielded cable to deliver strong and equal in strength TV signals to the home. A good quality antenna tower received TV channels from the airwaves and mapped them in the cable spectrum. In North America, bandwidth 50 to 550 MHz is reserved for NTSC analog cable TV broadcasts as shown in Figure 5.1. The 50 to 550 MHz range of frequencies is

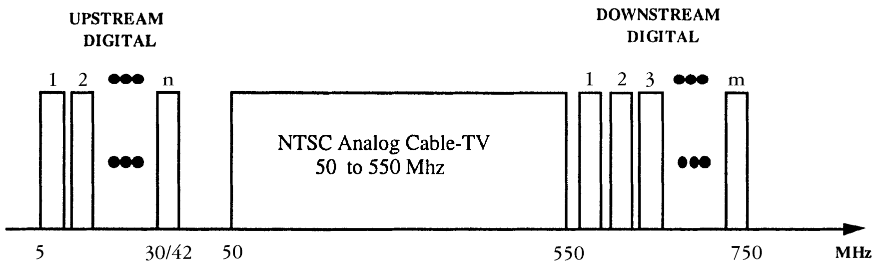

Figure 5.1 CATV cable spectrum

divided into 6-MHz channels (8-MHz for Europe). TV analog signals are modulated in each of the 6 MHz channels.

The TV signals in the cable coax are replicas of the ones broadcast through the airwaves, so no modifications were needed to the television set. CATV brought about yet another advantage. It could provide more channels, with signals of equal strength, to the end user than those delivered conventionally. TV signals lose power more readily in the air than in cable, and TV receivers and tuners cannot cope with the interference of more powerful adjacent TV signals.

Channel allocation in the spectrum is regulated by the Federal Communications Commission (FCC) which also regulates the frequency location and signal power used by TV broadcasters. These FCC rules guarantee that stations that use the same TV channel are far enough apart so as not to interfere with one another. Those rules coupled with the rapid attenuation of signal power in the air, enables cable operators to deliver more channels with equal signal power to homes.

Cable operators, by virtue of the increased market demand due to TV program variety and flexibility, and premium channel availability, were elevated from CATV operators to broadcasters, and later they became content providers. From the outset, the cable network evolved little if any in terms of two-way communication media. Lately, however, fiber optics installation, increased system reliability, and reduced operating and maintenance costs have accelerated. HFC modernization plans not only to set the stage for providing an infrastructure for bidirectional communication but also to increase channel capacity. With HFC modernization as a prerequisite, cable modem became practical to develop because the infrastructure was conducive to bidirectional communication and the high-speed interactive market was finally in demand and considered a normal part of society.

Regulation: Cable operators became more powerful as more and more homes subscribed to the service, and TV signals from metropolitan areas replaced local channels to make CATV more attractive to subscribers. At that time, the FCC began to regulate the industry and to dictate what an operator and which channels must be carried to serve the local community. The Cable Communications Policy Act of 1984 eased price control due to competition from broadcasters and encouraged growth. By that time, cable operators became content providers as well.

In 1992, the U.S. Congress passed the Cable Television Consumer Protection and Competition Act and reenacted price control regulation with some exceptions.

With the Telecommunication (reform) Act of 1996, Congress deregulated this industry with the proviso that the telephone industry could then compete in video services and the cable operators could also enter the local telephone service market.

5.3.2 Legacy Cable Network

The technologies of the sixties and seventies were readily available to provide CATV broadcasting services (one way). The networks were built independently to serve particular communities, so the economic model, more or less, dictated a simple and somewhat organized topology of a branch and tree architecture. A point-to-point approach was economically prohibitive and did not offer an advantage over a shared

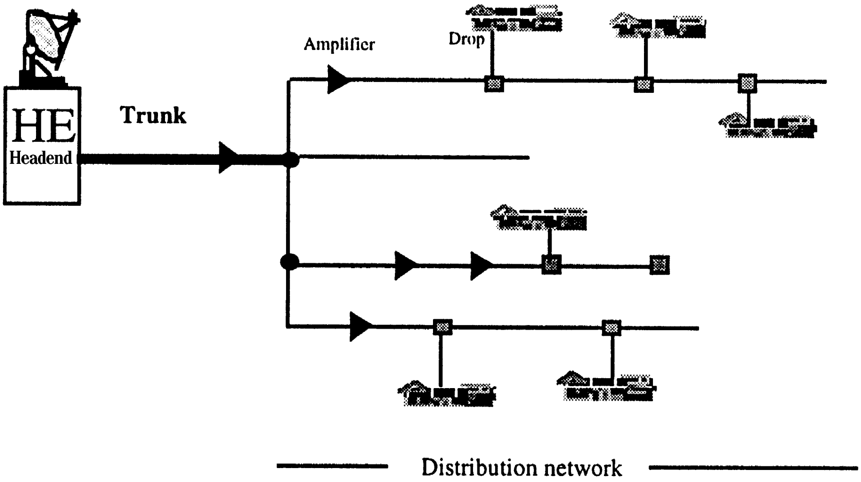

Figure 5.2 Cable system topology

medium access specially for broadcasting applications. Figure 5.2 illustrates a traditional cable network. The functional elements are

1. Cable TV headend
2. Long haul trunks
3. Amplifiers
4. Feeders
5. Drops

Headend: The CATV headend is mainly responsible for the reception of TV channels gathered from various sources, such as broadcast television, satellite, local community programming, and local signal insertion. These 6-MHz TV analog channels are modulated, using a frequency division multiplexing technique, and are placed into the cable spectrum as shown in Figure 5.1. This central control headend can serve thousands of customers using a simple distribution scheme. To achieve geographical coverage of the community, the cables emanating from the headend are split into multiple cables. When the cable is physically split, part of the signal power is split off and sent down the branch. The content of the signal, however, stays intact.

Trunks: High quality coax cables are used as trunks to deliver the signals to the distribution network and finally to its intended destination. The trunk can be as long as 15 miles. Lower quality coax is commonly used in the distribution and drop portions of the plant.

Amplifiers: TV signals attenuate as they travel several miles through the cable network to the subscribers' homes. Therefore, amplifiers have to be deployed throughout the plant to restore the signal power. The more times the cable is split and the longer the cable, the more amplifiers are needed in the plant. Excessive cascade of amplifiers in the network creates signal distortion. Amplifiers are also located in the distribution network (sometimes referred to as the *last mile*). These amplifiers, used in the traditional cable network, are one-way (amplifying signal from the headend to the subscriber). This scheme introduces several potential problems when a network needs to be upgraded to provide bidirectional communication. In such cases, these amplifiers need to be replaced with new two-way amplifiers.

Feeders: Feeders are sometimes referred to as the distribution network that serves the residential market. The term *home passed* usually refers to homes that are near the distribution network. The coax cables in the distribution network (branch/ tree) are usually short and are in a range of one to two miles.

Drops: Drops are usually located on telephone poles or more recently in a residential pedestrian area. A lower quality coax is used to connect from the drop to the home.

5.3.3 HFC Network

HFC (Hybrid Fiber Coax) was the next generation cable network (shown in Figure 5.3). HFC is the first step needed to provide bidirectional communications and it paved the way for serious cable modem deployments.

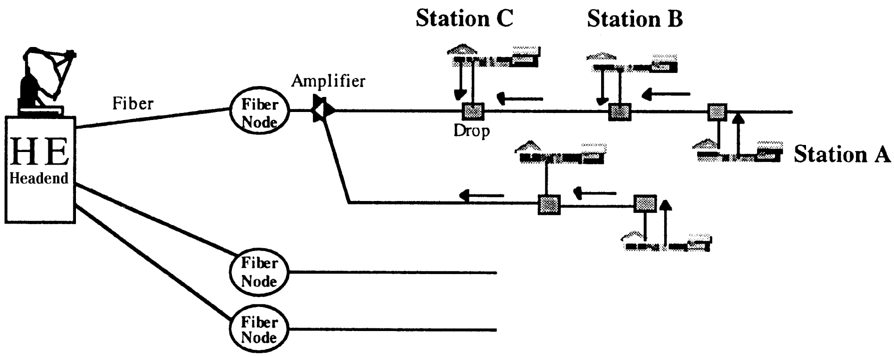

Figure 5.3 Hybrid Fiber Coax topology

HFC enhances a bidirectional shared-media system using fiber trunks between the headend and the fiber nodes, and coaxial distribution from the fiber nodes to the customer locations. The fiber extends from the access node to a neighborhood node. This fiber node interfaces with the fiber trunk and the coaxial distribution. It typically serves about 500 to 2000 (optimistic) subscribers via coaxial cable drops. These connected subscribers share the same cable and its available capacity and bandwidth. Because several subscribers share the same downstream and upstream bandwidth, special requirements such as privacy and security have to be taken into account.

Moreover, a special medium access control (MAC) scheme is required in the upstream direction, mainly acting as a traffic cop. MAC controls and mediates information flow, e.g., to prevent collision of information that is transmitted from users to the headend.

There are several other advantages of this HFC topology. The fiber trunk no longer needs amplifiers. Fiber is less immune to noise, and signal attenuation is practically nonexistent. These characteristics have the obvious advantage of increasing reliability, hence an amplifier failure affects only that particular residential area. Fiber deployment also means that far more bandwidth /channels will be at the disposal of the cable operator than would be available in the network for the subscriber.

5.3.4 Upstream/Downstream Cable Spectrum

In Figure 5.1, Frequency Division Multiplexing (FDM) is the scheme employed. In the upstream direction, the 5-42 MHz range is dedicated to digital transmission. In this direction, the cable modem as transmitter uses this range to transmit digital information from the users to the headend. In the downstream direction the 450-750 MHz frequencies are restricted for downstream digital transmission.

Cable modems must tune their receivers between 450 and 750 MHz to receive data digital signals. The digital data is modulated and placed into the 6 MHz channel (traditional TV signal). A cable modem, therefore, functions as a tuner. The QAM modulation scheme was selected by the industry for the downstream direction. In the upstream direction, the cable modem transmits the signal between 5 and 42 MHz. The data is modulated and placed in the 6 MHz channel using the QPSK modulation technique. At this frequency range the environment is very polluted and noisy because of interference from CB and HAM radios and impulse and ingress noise from home appliances. For that reason QPSK was selected as the modulation scheme. QPSK is more robust in terms of its immunity to noise, but at the cost of delivering data at much lower speed than other modulation techniques.

5.3.5 Digital Cable Network

All forms of communication today migrated or are migrating into digital format, e.g., CDs, cellular, voice, video. Most, if not all, future communication services are likely to be in digital format. The cable companies are under great competitive pressure to go completely digital. Digital transmission results in a noticeably better quality picture, at least noticable enough to be a differentiating factor for the consumer.

There is nothing inherent in the characteristics of cable or fiber pipes that prevents signals from being carried in digital format. Today's cable system can carry digital signals without modification as long as the modulated signal fits within the bandwidth and power constraints that the cable system carries. Digital communication can also co exist with analog TV signals as long as the digital signals are contained in their own 6 MHz band.

Using the cable network to transmit digital signals, including broadcast video signals, is of course possible. There is nothing in the cable network that specifically prevents such migration. Analog amplifiers in the system will be replaced with digital repeaters much like what the telephone network uses today to recondition the T1 digital signals. The advantage of going digital, in addition to improving signal quality due to noise, is the increased capacity of the cable system.

5.3.5.1 Potential Capacity

The cable system capacity will increase enormously if digital signals are transmitted instead of analog TV signals. The cable networks are built to support about 50 television channels. Cable channels should maintain 48 to 50 dB SNR in each 6 MHz channel. Modern modulation techniques such as Quadrature Amplitude Modulation (QAM) encoding, can achieve 43 Mbps capacity in a 6 MHz channel. The compression scheme used in the MPEG-2 standards for audio and video dramatically reduce the data rate required for transmission. A digitally compressed video signal of 3 to 6 Mbps can deliver an excellent quality broadcast video. So digital capacity of the cable system can potentially reach over 500 channels with existing cable bandwidth

5.3.6 Cable Network Modernization Effort

Modernizing the cable network to provide high speed interactive service is underway by most MSOs. HFC appears to have advantages over the other networks: its bandwidth capacity is enviable, and deploying a cable modem over a modernized HFC might be all it takes to be able to provide today's demanding, high speed interactive applications. A well-engineered cable modem can provide not only bidirectional data transmission but all the TV cable analog channels, high speed Internet access, voice, and high quality interactive video.

5.3.7 HFC Access Drawbacks

HFC is evolutionary and can be accommodated in a stepwise approach. However, access over HFC can also introduce a host of technically challenging problems. Cable operators must first and foremost address the service affecting problems when introducing integrated digital services. The most crucial ones are reliability, security/privacy, and operation and maintenance.

The HFC architecture, although cost effective, is not ideal when it comes to service reliability. The critical drawbacks are

- component failure in an amplifier in the distribution network can render the entire neighborhood out-of-service.
- AC power failure (powering the amplifiers) is a more serious problem that must be resolved.
- AC power outage can render the entire area out-of-service. AC backup for powering the amplifiers must be provided so customers can still make voice calls during power outage.
- Because of the shared medium topology, the action of a malicious user can affect the operation and communication of all those connected users

in the branch or tree in both directions. A failed cable modem may have the same effect (of disrupting the shared bus), but it is expected that the cable modem will be designed to isolate such failures.

- The upstream transmission path is prone to noise of all kinds. The entire cable network must be well-maintained to ensure that ingress noise is not leaking into the system, causing failures to users who are on the bus.

5.3.8 Factors Influencing Cable Modem Operation

5.3.8.1 Amplifiers Bidirectional Issues

Modern cable systems (HFC) with bidirectional communication must use amplifiers that work in both directions. To accomplish this, back-to-back amplifiers with filters are arranged so that downstream and upstream signals are first filtered then amplified. The upstream path has an inherent disadvantage because of the branch-and-tree topology. During amplification of the upstream, the splitter outputs become its input; the splitter simply combines the incoming signals and noise, hence both are amplified. In the downstream direction, the signals passing through a splitter are attenuated on the splitter outputs, but the noise carried downstream is also attenuated.

5.3.8.2 Frequency-Agile

A modem that is frequency-agile capable can tune into any one of the downstream or upstream frequencies. The cable modem in the upstream is able to transmit on whatever frequency the cable system is equipped to handle. This gives cable operators the tools to change the upstream and downstream bandwidth allocation spectrum in their system due to changing traffic demand, without user intervention or worse, having to change the terminal equipment. Excessive noise due to ingress (temporarily or long term) of an upstream channel can be dynamically isolated by simply retuning the cable modem to other downstream and associated upstream channel(s). A wider range frequency-agile cable modem for a single carrier (beyond the 5 to 42 MHz range) is implementation dependent. The expense of providing more complex agility may not justify the development cost. It will, however, offer a very flexible and robust cable modem.

5.3.9 Noise

The upstream channel in HFC networks has been the source of great concern. The channel frequency in which it must operate positions it in a very hostile noise environment. Ingress noise in the upstream direction is the main cause of impairments in an HFC system. This noise comes in different flavors and severity.

The industry developed a channel model that mathematically defined the nature and physics of the cable network noise. This model was used to refine the specifications of the physical and MAC layers for the cable modem.

The noise phenemenon environment in the cable network is unique. The cable system acts as giant antennae for various noises and impairments that are additive, especially in the 5 to 42 MHz band of the RF spectrum. Each type of noise must be combatted from its source before it propagates further into the network and mutates. Just as challenging is that the noise phenomena in the cable network are time dependent. What is measured in the morning is quite different from measurements made in the peak TV viewing hours. Moreover, these measurements are different from one region to the next. The age of the cable plant and drops in particular, humidity of the region, number of subscribers in the drop, inside-home wiring, and past maintenance practices, all play a part in how the network behaves under different loads. To say that the system must be developed for a worse-case scenario is not the optimal solution. In most situations, a field technician can enhance video signal quality and reduce noise measurably by mechanically and electrically securing the cable plant.

This presents a unique problem for the industry: noise measurements, to great extent, are based on field measurements. Hence, a cost effective solution in one region may unduly penalize other solutions in a less-current region.

In general, network noise problems come from three areas: the subscriber's home, drop plant, and rigid coaxial plant. Seventy percent of the problem comes from inside the home, 25% is generated from the drop portion of the network, and 5% is from rigid coaxial plant. Troubleshooting intermittent problems is costly and time consuming, and finding the problem does not always mean it can be fixed.

5.3.9.1 Noise Characteristics in the Upstream Direction

In the upstream direction, there are several noise sources that can impair upstream communications. A channel model was developed by the industry identifying these sources:

- **Hum Modulation** — Hum modulation is amplitude modulation due to coupling of 60 Hz AC power through power supply equipment onto the envelope of the signal.
- **Microreflections** — Microreflections occur at discontinuities in the transmission medium which cause part of the signal energy to be reflected.
- **Ingress Noise** — Ingress noise is the unwanted narrowband noise component that is the result of external, narrowband RF signals entering or leaking into the cable distribution system. The weak point of entry is usually drops and faulty connectors, loose connections, broken shielding, poor equipment grounding, or poorly shielded RF oscillators in the subscriber's household. Since the upstream transmission is at the lowest frequency of the network's passband, the noise summates at the trunk.
  Ingress noise contribution includes most, if not all, FCC-conforming RF power levels, such as hair dryers, power line interference, electric neon signs interference, electric motors, vehicle ignitions, garbage disposals, washers, passing nearby airplanes, high voltage line, power system atmospheric noise, bad electrical contact, and any open-air RF transmission such as CB and HAM radio transmission, leaky TV sets, RF computers, civil defense, aircraft guidance broadcasts, international shortwave, and AM broadcasters.

- **Common-path Distortion** — Common mode rejection is due to nonlinearities in the passive devices of corroded connectors in the cable plant.
- **Thermal Noise** — White noise is generated by random thermal noise (electron motion in the cable and other network devices) of the 75-ohm terminating impedance.
- **Impulsive Noise/Burst Noise** — Burst noise is similar to the impulse noise, but with a longer duration. It is a major problem in the two-way cable systems and the most dominant peak source of noise (a short burst duration — less than 3 seconds). Impulse noise is mainly caused by 60 Hz high voltage lines and any electrical and large static discharges such as lightning strikes, AC motors starting, car ignition systems, televisions, radios, and home appliances such as washers. Loose connectors also contribute to impulse noise.

  There are two kinds of impulse noise: Corona noise and Gap noise. *Corona noise* is generated by the ionization of the air surrounding a high voltage line. Temperature and humidity play a major role in contribution of this event. *Gap noise* is generated when the insulation breaks down or via corroded connector contacts. Such failures pave the way to the entry of lines discharge of 100 Kv lines. This discharge or arc has a very short duration (in μ sec) with a sharp rise- and-fall time period. The sources are most likely to be automobile ignition and household appliances, such as electric motors.
- **Phase Noise and Frequency Offset** — Phase noise arises in frequency-stacking multiplexers, which occur in some return path systems.
- **Plant response** — The cable plant contains linear filtering elements that are dominated by the diplex filters that separate upstream frequencies from downstream frequencies.
- **Nonlinearities —** Nonlinearities include limiting effects in amplifiers, laser transmitters in the fiber node, and the laser receiver in the headend.

5.3.9.2 Noise Characteristics in the Downstream Direction

In the downstream direction, there are several noise sources that can impair downstream communications. The noise sources, described below, are additive.

- **Fiber cable** — The fiber affects the digital signal in two ways:
  1. Group delay is due to the high modulation frequency of the signal in the fiber.
  2. White Gaussian noise is added to the power.
- **Plant Response** — Impulse response is defined as *tilt* and *ripple*. The tilt is a linear change in amplitude with frequency and is an approximation to the frequency response of the components in the network. The ripple is a sum of a number of sinusoidal varying amplitude changes riding on top of the tilt and is a measure of the effect of microreflections in the network.

- **AM/FM Hum Modulation** — AM/FM hum modulation is amplitude/frequency modulation caused by coupling of 110 Hz AC power through power supply equipment onto the envelope of the signal or shift both up and down in frequency.
- **Thermal Noise and Intermod** — Thermal noise is modeled as white Gaussian noise with power defined relative to the power at the output of the plant response. Intermod is caused by nonlinearities in the system generating harmonics of other channels.
- **Burst Noise** — Burst noise is due to laser clipping which occurs when the sum total of all the downstream channels exceeds the signal capacity of the laser.
- **Channel Surfing** — Channel surfing causes microreflections to appear and disappear. Because the significant sources of channel surfing are close to the receiver, a large but slowly changing ripple in the frequency domain will appear and disappear.

5.3.10 Approaches to Suppress Noise

There are many approaches to suppress or avoid ingress in HFC networks. Since these approaches are not mutually exclusive, they could be combined to improve the performance of the network. The guidelines shown below should be followed on a plant-by-plant basis. Network performance is affected for both the upstream and downstream channels, although the upstream channel is more pronounced in the overall performance.

- Aligning the amplifiers properly in the reverse direction.
- An important aspect of cable plant installation or modernization is to ensure the system is both mechanically and electrically sealed. For it to be otherwise will invariably cause a significant contribution to ingress and impulse noise within the system.
- All powered devices and the cable plant must be electrically grounded appropriately. This may prove difficult in arid and/or rocky climates due to the inability to establish a good electrical ground.
- Almost 70% of the source of ingress noise is generated at the subscriber drops. Low quality coax are used for the subscriber drops, and radial cracks and cracks in the shield's foil are the main source of leaks, hence ingress noise. The do-it-yourselfers are also contributing to system leakage when installing their in-home wiring, using older, bad, or loose connections. One effective approach to improving network performance upgrading adequate coaxial residential wiring and adding good connector and good grounding practices. This, however, may prove costly.
- Reducing the channel bandwidth adds robustness to the system because it reduces the group delay distortion and enables the use of higher order modulation schemes. This approach may not be economically feasible in some regions.

- A frequency agile cable modem (in a multitone carrier) is one method used to reduce (skip) noise impairments. It selects only the carrier frequency in the return path where noise is not present, that portion of the noisy return path spectrum will be marked as not usable. Fine frequency agile systems function well by avoiding noise; however, industry experts are divided and argue that, if such systems are fully adopted and deployed, they may become a liability when interactive services demand increasingly more bandwidth from the upstream resources. The argument maintains that frequency agility at the subcarriers is useful if the noise sources were a narrowband and not a broadband noise component. Ingress noise is the only type of noise that meets these criteria. Frequency agility is not an effective strategy for dealing with impulse or amplifier noise because the noise is broadband. This issue is described further in Section 5.2.5.2

5.4 CABLE MODEM

The previous section provided an overall picture of the cable environment and outlined the groundrules for developing and preparing requirements for the cable modem. This section describes the details of the cable modem.

Modern technologies, such as ATM, promise high speed integrated services for heterogeneous applications. With a broadband as the service kernel, network convergence will accelerate and, theoretically, one would no longer be able to distinguish one network from another. The Internet, a late market entry into the equation of the telephone and cable modernization plan, has a central but somewhat confusing role.

The current state of digital technology is such that we cannot fully predict how systems will be built. The quality of service needed, cost, and especially the uncertainty of the market demand for future applications and services are not fully predictable. With all such uncertainties, IEEE 802.14's approach was to develop a standard for a cable modem based on ATM and took advantage of our present understanding of quality of service (QoS) as it applies to ATM.

Multimedia Cable Network System (MCNS) and the Society of Cable Telecommunications Engineers (SCTE) developed a cable modem that is IP-centric, known as DOCSIS™ (Data Over Cable Service Interface Specifications). DOCSIS™ based cable modem bypasses the ATM layer (at least in its initial specification) hence it is IP-centric. In that context, two types of cable modems are under development by the industry:

1. Cable Modem that is ATM-centric
2. Cable Modem that is IP-centric

5.4.1 Standards Perspective

In 1994, the IEEE Project 802 executive committee approved the formation of IEEE 802.14 to develop a cable modem standard that is ATM friendly. That cable modem specification is expected to be released in the middle of 1999. IEEE 802.14 is presently working on a high speed physical layer (HI_ PHY) for the upstream channel (see Section 5.2.5.2).

Multimedia Cable Network System (MCNS) in conjunction with Arthur D. Little, Inc., developed a series of interface specifications for early design, development and deployment of data-over-cable systems. DOCSIS™ was one of the results of this group. The goal of the DOCSIS™ project is to rapidly develop an IP version of a cable modem and a set of communications- and operations-support interface specifications for cable modems and associated equipment over HFC.

The Society of Cable Telecommunications Engineers (SCTE) worked closely with MCNS and standardized the DOCSIS™ version of the cable modem. It is also involved in the development of standards for digital video signal delivery through coordination of efforts with NCTA, the FCC, and others.

5.4.1.1 ATM-based vs. IP-based Cable Modems

Architecturally and philosophically, ATM-centric and IP-centric cable modems use similar technology. The physical layer of both cable modems is identical and based on ITU J.83 (with some exceptions for North America). The fundamental difference between DOCSIS™ and the IEEE 802 cable modem is in the development of the MAC layer and the layers above. Unlike DOCSIS™ the ATM-based cable modem MAC layer contains the segmentation and reassembles (SAR) necessary for ATM end-to-end operation. For IP services, IP over ATM uses AAL5's SAR to contain the IP packet. DOCSIS™ on the other hand, uses variable packet (IP-packet) as the transport mechanism per ISO8802-3.

Other differences between the ATM and IP-based cable modems lie in the functionalities of the upper layer interface services as well as security, maintenance, and management messages (e.g., registration and initialization).

Such differences may be considered major, but some vendors are considering the idea of providing glues to accommodate both ATM-based and IP-based cable hardware in silicon. Although this is possible, especially because the physical layers are similar, it is unlikely to have a cable modem with dual personality if only because of the stiff competition that will be ruling the market.

The differences between the IP- and ATM-based cable modems will be noted when warranted, as we describe the various functional components.

5.4.2 Abstract Cable Modem Operation

The technical challenge of developing a cable modem that will deliver integrated services over cable is significant. Sharing access among multiple users creates security and privacy problems. One user connected to a cable network can possibly receive transmissions intended for another or maliciously make transmissions pretending to be another user. As such, all components of the cable modem are providing the hooks for the management and security for the system. The basic generic description of the cable modem below hides all that complexity but provides an initial operational understanding of a cable modem.

The primary function of the cable modem is to transport high speed digital data from the cable network to the users, and from users to the cable network. Figure 5.4 depicts the physical landscape and interface negotiation between a headend and the cable modem. Cable Modem # x denotes the number of cable modems that are attached to the subnetwork. Depending on the traffic, 500 to 2000 typical homes might be served in this topology. At the channel level, the cable modem in the downstream direction must tune its receiver between 450 to 750 MHz, at the 6 MHz band, to receive data digital signals. In this example *m* downstream channels are available in the cable subsystem. The QAM modulation scheme was selected by the industry as the modulation technique for the downstream direction.

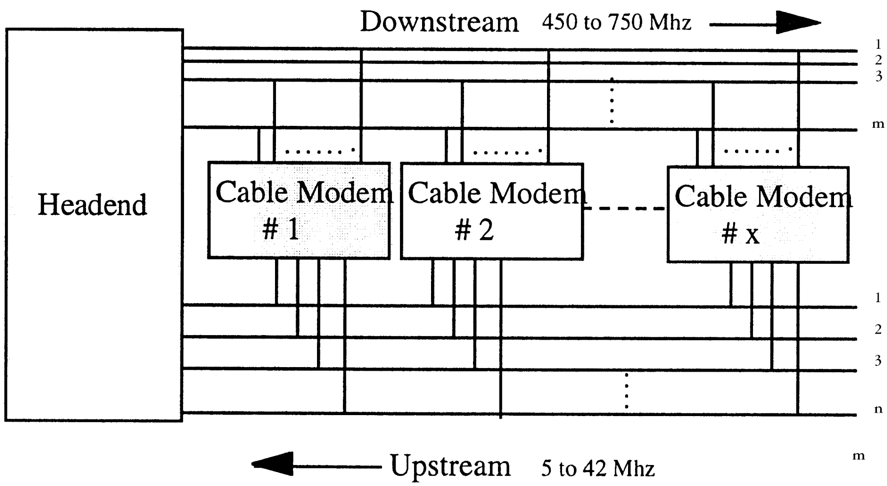

Figure 5.4 Cable Modem/ Headend Physical Topology

In the upstream direction, the cable modem performs the transmitter function, transferring information to the headend using the 6 MHz band between 5 and 42 MHz. In this example, *n* downstream channels are used to transmit upstream data. The data is modulated and placed in the 6 MHz channel using the burst QPSK modulation technique. At this frequency range, the environment is very noisy because of interference from CB and HAM radios and impulse and ingress noise from home appliances, as described in Section 5.3.10, which is why QPSK was selected as the modulation scheme. QPSK is more robust in terms of its immunity to noise, but at the cost of delivering data at a much lower rate.

Basic operation — A cable modem must be able to tune into any one of the downstream 6 MHz 1 to *m* bands to receive data from the headend. At the transmitting end, the cable modem must also be able to transmit at any of the downstream channels from 1 to *n*. A dialog between the cable modem and headend is triggered when a station requests registration to join the cable network (to be attached). There are certain associations between the downstream channels *m* and upstream channels *n*. Depending on the cable network span and traffic engineering, downstream channel 1 may be associated with one or more upstream channels.

During registration to join the network, a cable modem automatically starts listening to the downstream channels seeking entry to register its device. When the cable modem receives a strong signal, it reads the subsystem frequency allocation layout and sends a request to register to the headend using one of the assigned upstream channels. Once acknowledged by the headend, ranging, authentication, and initialization begins in order to legitimize the cable modem and provide the subscribed services. Plug-and-play is the philosophy used to get the modem operational.

Cable modem speed — Depending on the cable noise environment, typical bandwidths of 36 to 43 Mbps can be delivered to the cable modem in the downstream direction with the 64-QAM modulation technique. In the upstream direction, QPSK modulation can deliver up to 1.5 Mbps speed. In a shared-medium environment such bandwidth is shared by many users who will be competing for access to the same upstream channel or channels. The most critical path in the upstream direction (many-to-one) is the modem MAC. MAC arbitrates access in this shared-medium bus and allocates the requested bandwidth. The bandwidth allocated to a user in the upstream direction will invariably depend on the number of users sharing the bus. It will also depend, to a large extent, on the characteristics of the traffic being used by others who are sharing the bus. If congestion is encountered, a smart cable modem can retune its receiver and hop to a different upstream channel, when instructed to do so by the headend. This mechanism is referred to as a *frequency agile capable* cable modem.

5.4.3 Cable Modem Layer Architecture

The reference architecture is the building block and the blue print that is needed to construct any device. The reference layer architecture for a cable modem is as shown in Figure 5.5 and contains

- Physical (PHY) layer
- Mac Layer
- upper layers

The layers are described below, followed by details necessary for having an operational understanding of a functional cable modem.

5.4.3.1 Physical Layer

The physical interface for digital cable systems is the ordinary coax cable. This physical layer contains both the upstream and downstream channels. Upstream transmission is more difficult than downstream transmission because of the shared-medium access collision and the multitude of noise that pollutes that spectrum (below 42 MHz.) To some extent this noise problem can be compensated for by using complex encoding technologies at the cost of reducing the data rate. Hence,

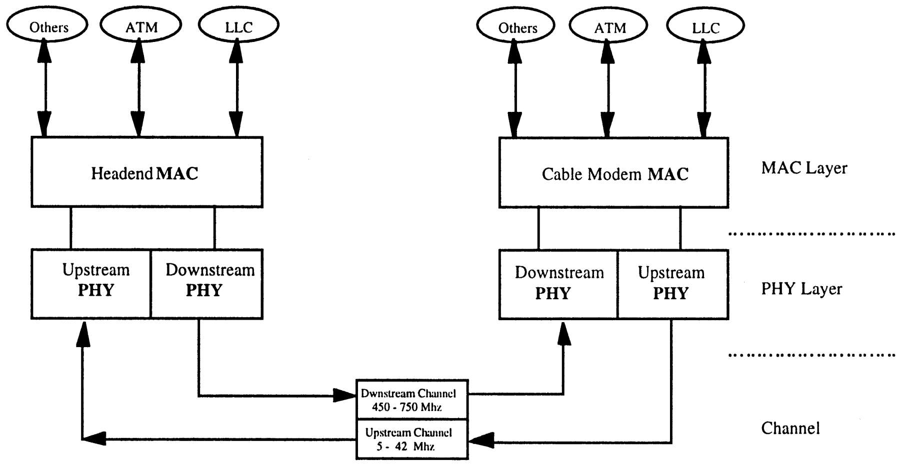

Figure 5.5 Cable Modem / headend Layered Architecture.

a digital cable architecture may use only one downstream transmitter at the header and has several associated upstream transmitters. Transmitters are more expensive than receivers.

5.4.3.2 MAC Layer

The MAC layer is the most challenging to ascertain and has been and continues to be the topic of discussion in the higher educational community. The complexity arose because of the shared medium coupled with the requirement to maintain QoS for each connection of the user application.

In the upstream direction, the communication path is shared by many active users, all transmitting data to the headend. A fundamental function of any MAC is to devise a mechanism that performs random access to the network, resolves contention, and arbitrates resources when more than one station wishes to transmit at the same time. The MAC is further burdened by the requirement to preserve the QoS of any and all specific applications. If real-time video or voice is being transmitted, the jitter must be minimized and a bandwidth of constant bit rate (CBR) must be allocated. Unlike data packets, if delayed only slightly a real-time voice packet becomes useless.

The MAC for the cable modem offers much more challenging opportunities because it must operate under a much more hostile environment than any previous MAC developed so far: a public environment where QoS and user expectations are of paramount importance. The cable modem MAC must deal with interactive and multimedia services with bandwidth-hungry applications requiring a multitude of service requirements.

Several cable modems are on the market today, and most if not all deal with service-specific applications. Market pressure also yielded MAC specifications that deal exclusively with service specific applications, particularly for the Internet. However, just speeding the access interface, such as for a cable modem, does not solve the multimedia service requirement. The concept of QoS must be embedded in the development of a MAC protocol so it can operate to the satisfaction of the end users. Market dynamics are very unpredictable and confuse short term planners.

5.4.3.3 Upper Layers

The cable modem should be designed to handle all management entities and service interfaces, be they IP, native ATM, or others.

IP interface — The cable modem can connect directly to a PC handling IP traffic. The physical layer, to the end-user, will most likely remain Ethernet 10BaseT, the predominant method. Although it probably would be less expensive to produce the cable modem as an internal card for the computer, doing such would require different modem cards for different computers. Moreover, it would further confuse the demarcation between cable network and the subscriber's computer.

ATM-native interface — The cable modem being standardized by IEEE 802.14 is designed to handle native ATM services. That means, ATM adaptation layers will be developed to handle ATM applications, including CBR, VBR, and ABR services, among others.

5.4.4 Cable Modem Fundamental Layers

The critical components of any cable modem, as shown in Figure 5.6, can best be described mainly using the two fundamental layers: the physical layer and MAC layer. Both of these layers will be imbedded mostly in the hardware. Software in the cable modem will complement all other layers to give it its service personality. It is worth noting that the MAC/ATM convergence sublayer (SAR) will *not* be present for the IP-based modems. A bottom-up approach is used to describe details of the two layers. These layers and sublayers define the dialog needed between the headend and cable modem.

5.4.4.1 Physical Layer

The physical layer, shown in Figure 5.6, contains two sublayers: the physical medium-dependent (PMD) sublayer and the transmission convergence (TC) sublayer. These sublayers take on the personality of the attached transmission link to perform the needed bit translation, synchronization, orientation, and modulation functions. Figure 5.7 shows the landscape of the sublayers and associated functionalities of each.

5.4.4.1.1 PMD Sublayers

The main function of the PMD sublayer is to modulate/demodulate the RF carriers on the analog cable network into digital bit streams, perform synchronization,

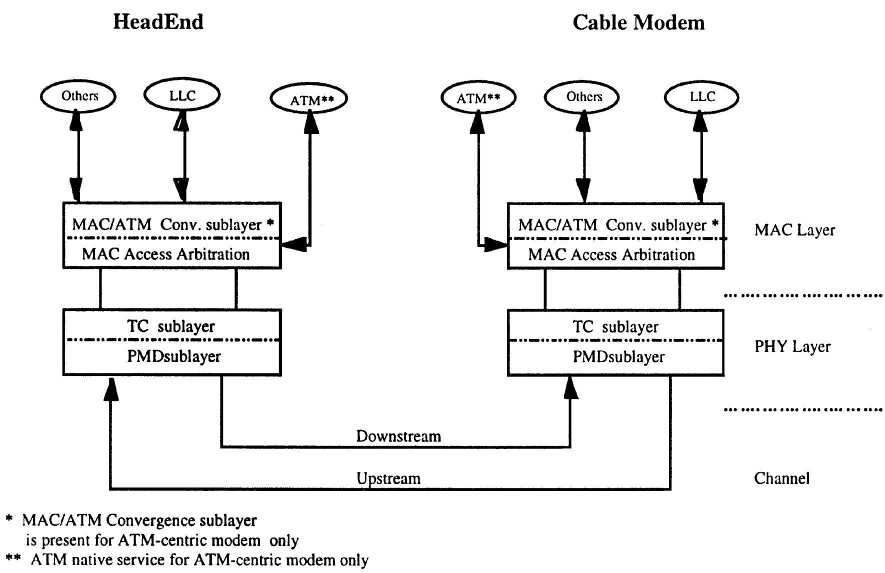

Figure 5.6 Fundamental layers of a cable modem

. MPEG 188-0ctet per ITU-T H.222.0 . Mpeg synchronization & recovery . Mpeg PID Muliplexing/ Demultiplexing . Delineation of PDUs & scrambling . Controls: Ranging; Power; Synchronization, etc		**TC**	**Physical Layer**
DOWNSTREAM	**UPSTREAM**	**PMD**	
. Scrambler . Reed-Solomon encoder . Interleaver . Differential encoder . RF. QAM modulator per ITU J.83	. Data to codeword conversion . Reed_ Solomon encoder . Scrambler . Preamble generator . Pulse Phasing . QPSK or 16-QAM Modulation		

Figure 5.7 Sublayers of the physical layer (cable modem perspective)

coding, and error checks. The ITUJ.83 recommendation was adopted for the NA as the base. The PMD, as shown in Figure 5.7, is further subdivided into two sublayers:

- downstream PMD
- upstream PMD

Because of space limitations, a full discussion of the PMDs is not feasible. Readers are encouraged to read ITU J.83 for the full technical specifications and critical time requirements. However, a brief description of the downstream and upstream PDMs is provided below.

Downstream PMD — Downstream PMD modulates and demodulates the RF carrier using QAM modulation techniques, a means of coding digital information over radio. ITU-J.83 specifies three types of downstream interfaces: type A, B, and C. Type B of ITU J.83 is the downstream as shown for this example. The cable modem supports both 64 and 256-QAM. At 256-QAM the nominal symbol rate value is at 5.360537 Msym/sec (baud rate). At 64-QAM the nominal symbol rate value is at 5.056941 Msym/sec. Nominal channel spacing is 6 MHz and center frequency is specified at 91 to 857 MHz.

Upstream PMD — The upstream PMD sublayer supports two modulation formats: QPSK and 16-QAM. The modulation rates of the modulator provide QPSK at 160, 320, 640, 1,280, and 2,560 ksym/sec, and for 16-QAM at 160, 320, 640, 1,280, and 2,560 ksym/sec. The upstream PMD supports a frequency range of 5 to 42 at 6 MHz of the subsplit. The range for European cable plants is, 5 to 65 MHz, and the Japanese range is 5 to 55 MHz.

Other functions performed in the upstream and downstream PMD layers are designed to transform FDM to TDMA. It will also improve the efficiency and robustness of the transmission by mitigating the effect of burst noise, using encoders to make phase rotation insensitive to QAM constellation, randomizing the transmitted data payload, correcting symbol errors within the information block (codeword), synchronizing, and establishing a TDMA landscape. For the upstream, it performs pulse shaping and a variable-length modulated burst with precise timing beginning at boundaries spaced at integer multiples of 6.25 μsec apart.

5.4.4.1.2 Upstream Frame Structure

Immediately after the PMD sublayer's bit stream is processed, the frames begin to emerge and the information looks more comprehensive. The TC (Transmission Convergence) sublayer refines the information further, especially for the downstream, and processes it into formats readying it for further data processing. The frame format of the upstream is described below.

Characteristics of the Upstream frame — The headend generates a time reference identifying slot in the time-domain. The slot containers, in the upstream, enable a cable modem to transmit information to the headend. Based on that time reference measured in 6.25 μsec ticks, a minislot is then created whose size is of this time tick. The duration (in time) of one minislot will equal the time required to transmit 6 octets (programmable) of data plus the time required to transmit the physical layer overhead and the guard time.

A MAC layer Protocol Data Unit (PDU) occupies a single minislot known as a MiniPDU. The upstream landscape can be thought of as a stream of minislots. Minislots are identified and labeled using a free running counter assigned by the headend and incremented by the master clock tick. The headend determines the usage of each minislot in each of the upstream channels. This information is conveyed to the cable modems by broadcasting their usage using the downstream channel in a form of a map or image reflection.

Several minislots can be concatenated to form a packet, as shown in Figure 5.8. For an ATM-based cable modem, consecutive minislots are used to form and transport an ATM cell to the headend. For an IP-based modem, minislots are allocated consecutively to form a variable-length packet for transmission.

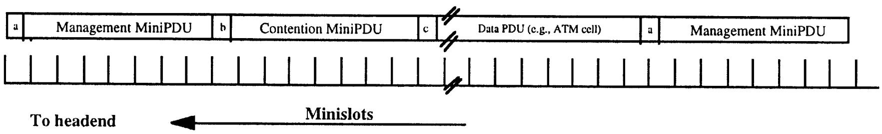

Figure 5.8 Minislots landscape for the upstream

There are various personalities defining each of the MiniPDUs. An information element in the MiniPDU (shown in Figure 5.8 with header a, b, or c) defines the various functions allocated. A MiniPDU can be used as management messages for ranging or RF power adjustment (between the headend and cable modem), the Mini PDU may be requested by the cable modem to vie for access to the shared medium, or the MiniPDU may be a portion of a payload of a data PDU.

The number of minislots required to carry an ATM cell depends on the length of PHY overhead and guard time required by the upstream PHY (per the MiniPDU burst profile). For the ATM-based cable modem, an integral number of minislots are allocated by the headend to transmit an ATM cell.

5.4.4.1.3 TC (Transmission Convergence) Sublayer

For the downstream, the TC sublayer refines the data further, and the bits are assembled and massaged to fit into a frame.

5.4.4.1.4 Downstream Frame Structure

For the downstream frame structure, the industry adopted ITU-T H.222.0. It is defined as the MPEG-2 (MPEG) packet format with 4-byte header followed by 184 bytes of payload (totaling 188 bytes). The header (PID field) identifies the payload as belonging to either DOCSIS™ or IEEE 802.14-based MAC. Figure 5.9 illustrates the cable modem MAC frame, interleaved with other digital information payload(s). The interleaving rate must take into account the jitter that may influence service profiles. A constant rate of interleaving (1: n) is suggested (i.e., one cable modem Mac payload for every *n* digital video payload).

The digital video information payload in the downstream, MPEG-based, was not an accident. It was designed so it can be provisioned for use when the cable

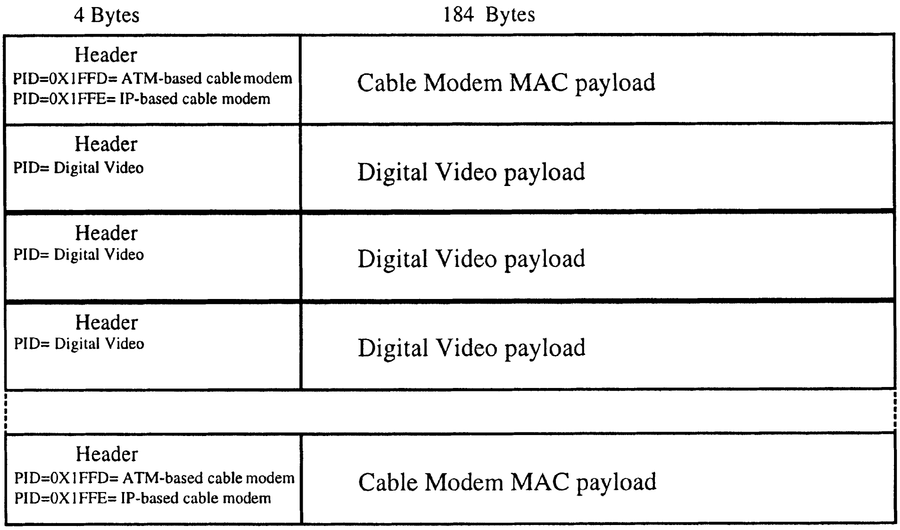

Figure 5.9 Frame format for the upstream

network evolves into a digital format with common receiving hardware accommodating both video and data. This provides an opportunity for possible evolution to digital as described in Section 5.1.3.5.

The first order of business of the TC is to establish synchronization and identify the MPEG frame boundaries which is accomplished by the TC hardware (of the cable modem). When entering the hunt state, the hardware in the TC shifts, calculates, and seeks the correct CRC of the MPEG payload. Five consecutive correct parity checksums of the 188 bytes declares the MPEG packet *in frame*. *Out of frame* is declared when 9 consecutive incorrect parity checksums are received.

Once the MPEG frame boundary is established the TC extracts the cable modem packet data from the MPEG payload. The format is shown in Figure 5.10.

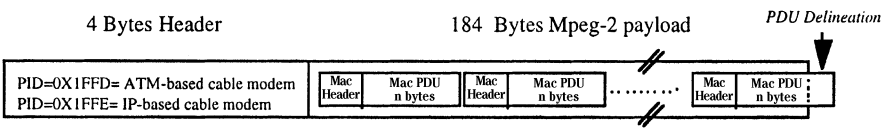

Figure 5.10 Downstream frame embedded in the MPEG frame

Beyond this point, the similarities between the ATM-based cable modem and IP-based cable modem end. Although philosophically and fundamentally they are similar, the data interpretation and manipulation differ in a number of ways. As Figure 5.10 shows, for an ATM-based cable modem each PDU within the MPEG frame is fixed in length and, in fact, is an ATM cell.

For the IP-based cable modem, the PDU payload is variable in length and conforms to ISO8802-3 type PDU.

PDU delineation (where a PDU traverses from one MPEG frame to the next) is supported on both cable modems. For the ATM-based cable modem, the PDU boundaries (ATM cell) are marked using the procedure described in ITU-T Recommendation I.432. In summary, HEC (Header Error Control) checksum will be responsible for identifying cell boundaries. Once in the hunt state, the reception of seven consecutive and correct HEC (on the five ATM header bytes), marks the boundary of the cells that are in a frame, in which case it declares the PDU *in frame*. *Out of frame* is declared when five consecutive HEC errors occur, in which case the TC will then go into hunt state, again, to establish the cell boundary.

MAC PDU boundary for the IP-based cable modem uses pointer_field. The pointer_field is the first byte of the MPEG payload (not shown in Figure 5.10) and may be present to point to the start of the next MAC PDU. The header indicates if the pointer_field must be used. With this approach MAC PDU may begin anywhere within an MPEG packet, a MAC PDU may span MPEG packets, and several MAC frames may exist within an MPEG packet.

Low level initialization — Once the PDU framing and formats are established the TC begins performing initial low level tasks such as synchronization, ranging, and power adjustments. To accomplish this, two fundamental pieces of information are needed by each cable modem: global timing reference to all modems and timing offset. Similarly, the attenuation from any cable modem is most likely different from another and from the headend. Therefore, each must properly adjust its power level for its transmitter such that all stations' transmissions reach the headend at approximately the same received signal level.

Synchronization — Once the cable modem successfully assembles the frames (by the TC as described above), it then must synchronize its clock with the headend clock. This is performed when the headend (periodically) sends a management message containing a global timing reference. The management message contains the timestamp identifying when the headend transmitted this reference clock. The cable modem compares it with its own time and adjusts its local time accordingly. The cable modem periodically adjusts its local clock.

Ranging and power adjustment — Once synchronization is established, the cable modem must then acquire the correct timing offset such that the cable modem's transmissions are aligned to the correct minislot boundary. In other words, it adjusts the cable modem timing offset such that it appears to be located right next to the headend (without delay).

First the cable modem must learn the map of the available upstream channels so it can send an initial management message to the headend to perform the ranging. The initial maintenance region slot demarcation (subsequent to ranging) is large enough to account for the variation in delays between any two cable modems. When the initial maintenance transmits opportunity occurs, the cable modem sends the ranging request message.

The headend responds with a ranging response message addressed to that particular cable modem. The response message contains the needed information on RF power level adjustment and offsets frequency as well as any timing offset corrections.

A dialog is then established again to fine-tune and correct both the power and timing offset of the cable modem.

5.4.5 High Speed Physical Layer

IEEE 802.14 organization is working with SCTE/MCNS on a new HI_PHY for the upstream. Experts from both organizations are studying several proposals to specify a new high speed upstream physical layer that will accommodate, without changes to existing upper layers, DOCSIS™ cable modem, as well as the IEEE 802.14 cable modem. The HI_PHY specification is expected to be released in 1999.

Discussion revolves around whether a frequency band (e.g., the 6 MHz) should be divided further into a discrete set of frequencies and carry the data in the upstream direction. It is worth noting that 6 MHz is an arbitrary value the industry used; one can use any value.

Frequency agility, described in section 5.1.3.8, is in this context a coarse agile cable modem. For example, the cable modem, upon request from the headend, hops to a different upstream channel to a 6 MHz increment. The advance (fine) frequency agile cable modem can tune its carrier frequency to multiple subfrequencies with very low resolution. The intention is to evade and selectively ignore that portion of the band in which the noise becomes excessive or intolerable.

This DMT (Discrete Multi-tone) technology was adapted for ADSL but not necessarily because of the noise environment.

Other proposals argue for the use of a single carrier approach (e.g., 6 MHz) with a high density modulation scheme and a front-end filter. This scheme abates the ingress noise while deploying a higher coding efficiency of QAM that can be dynamically changed with the changing noise environment.

Preliminary analysis suggests that the varying solutions are not necessarily superior to the present single carrier approach (assuming higher order QAM) as described in Section 5.4.5.1.1.

Each of the approaches has benefits in terms of noise assumptions, but behave less so in the different noise characteristics, as described in Section 5.3.10.

The idea for the next generation cable modem, of using a TDMA system (single carrier) with adaptive and dynamic changing constellation size, is attractive. The headend continuously monitors the channel noise and adjusts the constellation size accordingly.

It is too early, however, to discount other solutions yet. Experts are studying the noise dynamics of the cable plant more closely so they can select the best suitable solution. Cost and complexity will no doubt play a role in the eventual outcome.

5.4.6 Overview of MAC

One of the main functions of a MAC is a collection of upstream and downstream channels for which a single MAC allocation and management protocol operates. Its working environment includes the headend and all other connected modems.

The headend services all of the upstream and downstream channels.

One can think of a MAC protocol as a collection of components, each performing a certain number of functions. A cable modem MAC protocol can be broken into the following sets of critical components: acquisition process, message format, support for higher layer traffic classes, bandwidth request, bandwidth allocation, and contention resolution mechanism. The message format element of the MAC defines the upstream and downstream message timing and describes their contents.

The MAC layer in the cable modem may contain sublayers. For an ATM-based modem, the MAC sublayer contains the SAR which is used to assemble or disassemble ATM cells from the non-ATM service application (e.g., IP over ATM). Hence, it provides the interface for the upper service layers, be it IP-based or native ATM. This was illustrated in Figure 5.6.

The main feature of the MAC, however, is its ability to support the transfer of packets while maintaining the ability to provide QoS. The upstream channel is a precious resource, so collision and data flow must be managed very efficiently. The upstream channel is divided in time into basic units of minislots, of which there are several types. Their function is defined by the headend and conveyed to each cable modem by means of downstream control messages. Several minislots can be concatenated in order to form a single data PDU, or ATM cell. There is no fixed frame structure, and there is a variable number of minislots in any given time. Thus the upstream channel is viewed as a stream of minislots. The MAC layer also contains the controls and rules governing information processing and flow control. Management messages are defined to handle various tasks, primarily the interaction between the cable modem and headend for modem initialization, authentication, configuration, and authorization.

To the extent possible, plug-and-play is the philosophy adopted to perform these tasks.

Some critical examples of management routines and dialog between the headend and cable modem are provided below.

5.4.6.1 Initializations at the Upper Layers

Channel Acquisition — Channel acquisition is the process already described above. Once a cable modem accomplishes its synchronization and framing, and established communication with the headend it has completed channel acquisition. Depending on traffic distribution, the headend may request the cable modem to change its channel(s). The headend acts as the traffic cop and could instruct the cable modem to change either the upstream or downstream channel(s). The cable modem must respond and re-initialize at the PMD and TC layers. Once accomplished, channel acquisition is completed.

Registration — During registration several messages are exchanged between the cable modem MAC and headend to legitimize entry of the cable modem in the network so it can be declared operational.

If channel acquisition, ranging, and power leveling were performed, a cable modem must first register with the headend. This starts the MAC registration process. The cable modem is assigned a temporary service ID that has only local significance. This ID will be associated with the cable modem IEEE 802 - 48-bit MAC address which is assigned during the cable modem manufacturing process. It is used to identify the modem to the various provisioning security servers during registration.

5.4.6.2 Security and Privacy in the HFC Network

The security and privacy problems for HFC are different from the traditional point-to-point wireline networks. In the telephone environment, the copper wires are dedicated to the user and connected directly to a line card at the central office. Eavesdropping on a telephone line cannot be done as easily as in a shared-medium line. It certainly cannot be monitored by users in other homes. Registering a device illicitly (service theft) on a dedicated line is nearly impossible. The operator knows the identity of that line because it terminates physically at the site. In a cable network environment, the security problem is more difficult because many stations have physical access to the same wire.

Understandably some in the cable industry question the need for privacy and the added complexities to provide it. The cable telephony, for example, could fall under the same category as cellular, cordless phone, or PCS. Eavesdropping on these systems can be done just as easily, if not more easily, as in the cable modem. It can then be argued that if a cable phone is to be used, privacy and its associated complexity may no longer be considered necessary. After all, not long ago, even copper wires were shared among several telephone users. Distinctive ringing was used to identify the called party.

Security requirement at the MAC — Provisions were made on the cable modem to specify the access security mechanisms so as to make the security of shared-media access networks comparable to that of nonshared-media access networks. The process is basically to exchange a secret key during registration in which a cable modem sends it unique ID (IEEE 802 - 48-bit MAC address) to the headend, then proceeds with a secret key exchange to register. The certification ID is simply used as authenticity (e.g., initial password) prior to the secret key exchange that will follow. If the headend is not provisioned to accept this ID then registration fails. A hacker using a legitimate ID (an illicitly obtained secret key) would be able to register as long as the legitimate user had not registered first. During this registration process, the ID information is transmitted in the clear so a hacker would be able to listen to a successful registration transaction and record the ID information.

Secret key exchange — The secret key exchange uses the Diffie-Hellman exchange during the registration process to establish a common secret key. The authentication procedure incorporating the secret key is used to verify the identity of the station to the headend. A hacker who obtains a legitimate ID number of the device would also need to obtain the correct secret key. IEEE 802.14 adopted the Diffie-Hellman key exchange procedure.

Maintaining station keys — A cable modem is usually equipped with more than one separate encryption/decryption secret key. They are exchanged during registration by means of *cookies* which are exchanged between the cable modem and headend during registration/authentication routine when entering the network or at any time the network operator deems necessary. A 512-bit ephemeral Diffie-Hellman is used for main key exchange which produces a cookie.

This process, however, does not differentiate between a newly subscribed user with which it has not established a cookie yet. A hacker may very well be able to establish a network connection using a clone MAC address (or an illicitly obtained one) during registration. This, however, is a futile exercise for the hacker because the legitimate user will be denied access to the network when attempting to register. This denial of service to the legitimate user will prompt the operator to perform authentication by other means such as personal intervention, thus revealing the attacker and remedying the problem.

5.4.6.3 Fundamentals of Collision Resolution

MAC operation, in terms of flow control, describes the entry mechanism and steady state operation of the station's behavior. In the shared-medium environment communication is many-to-one. Subscribers compete on the shared-medium bus to get the attention of the headend so it can be granted permission to start sending the data. MAC controls the behavior of users who want to access the network as well as honor the service contract promised by the application and network. Hence, MAC arbitrates the communicating path and resolves any collision that occurs. The headend acts as a central office in that it controls and mediates all communications between, and/or from, all connected cable modems.

There are several MACs developed and specified in the public and private networks. The two contention/resolution mechanisms are the time division multiplexing access and collision resolution like contention and collision resolution mechanism (CDMA).

Time Division Multiplexing (TDMA) — In the TDMA approach, each connected device is allocated a timeslot in a specified timeframe. The frame contains a fixed number of time slots and each will be dedicated exclusively to one of the connected devices. When a device has data to send it uses its dedicated timeslot to send the information at its leisure. The obvious advantages of this mechanism are

- no collision is experienced in the shared medium so no contention resolution is needed,
- it is the ideal solution for constant bit rate traffic like voice or video telephony, and
- it gives fair access to all connected subscribers.

The disadvantages of TDMA are also obvious:

- An idle user's timeslot is unduly wasting network resources. In most multimedia applications the traffic is bursty and unpredictable, whether the subscriber is on the Internet, sending e-mail, or on the WWW clicking the icons. In this case the allocated timeslot is used occasionally. Providing full time access to stations in such a premium and limited upstream channel is a waste and may become prohibitively expensive.

Contention and collision resolution mechanism: In the contention and collision approach, the mechanism assumes that devices, when they need to, must vie for accessing the bus so it can send data. MAC responsibility is to arbitrate the access, resolve contention, and control the traffic flow. Consequently, the shared bandwidth is used only when needed, efficiently using the upstream resources. Collision is certain to occur, especially in a folded architecture. The device retries until it gets access. This mechanism is well known and serves the data transaction very well (it is not delay sensitive). QoS, fairness, and effective use of resources are not fully addressed in this mechanism.

5.4.6.4 Cable Modem MAC-Bandwidth Allocation

The above discussion suggests that a hybrid of both the TDMA and reservation/contention mechanism will best serve a multimedia application. Both the IP-based cable modem and ATM-based cable modem adopted this technique, but they differ in the collision resolution algorithm solution.

The headend algorithm is responsible for computing bandwidth allocation and granting requests. The flavor on the number of request slots/grant combination is vendor-implementation specific.

The MAC protocol description concentrates on the following issues:

- Upstream bandwidth-control formats define the request minislot types and structure.
- Upstream PDU format describes the protocol data unit format for ATM PDUs segmented into variable-length fragments for an efficient transport of LLC traffic types.
- Downstream format specifies the downstream data flow that can be seen as a stream of allocation units, seach 6-bytes long. As mentioned earlier, ATM cells can be sent by concatenating several basic minicells together. Each ATM cell can carry a number of information elements such as bandwidth information elements: grant information, allocation information (request minislot allocation), and feedback information (request minislot contention feedback).

5.4.6.5 Request for Upstream Bandwidth

The headend is responsible for allocating transmission resources in the upstream channel to cable modems that are queued for contention-based reservations. Each cable modem vies for access to obtain its share of transmission resources. One or more logical queues may contend for access from a single cable modem to serve the need of multimedia applications (several connections within a session with different QoS).

Each cable modem has various means of requesting bandwidth from the headend. Initially, the modem requests bandwidth through contention-based transmissions on the upstream channel. Once the headend grants the request, additional bandwidth may be requested by the cable modem by setting a bit (in the appropriate field) in the data PDU in transition. This method is known as *piggybacking*. It is most useful when contention access delay is high. A CBR permanent allocation can be requested by a cable modem for a logical queue, such that periodic grants at a desired frequency are allocated until the cable modem sends a CBR release message.

Request Minislots (RMSs) are allocated in the upstream channel by the headend to the cable modems for contention access. An RMS grant message identifies a number of RMSs divided into groups for different distinct sets of MAC users which are at various stages of contention resolution.

Typically, the headend allocates more than one RMS to each cable modem, and an RMS may be allocated to multiple MAC users. To reserve transmission resources in the upstream channel, a MAC user randomly selects an RMS from the group of RMSs available to it then attempts to send a request message in the selected RMS. The request message, referred to as a Request MiniPDU (RPDU) identifies the MAC user and the size of its requested allocation. Since the MAC user does not necessarily have exclusive access to the RMS, collisions can occur in which case a contention resolution algorithm is invoked to resolve it. The contention resolution algorithm for the ATM-based cable modem is based on a tree splitting algorithm and is specified with a flexible framework that permits a number of variational implementations. For IP-based cable modems, the contention resolution is based on a binary exponential backoff algorithm.

If the MAC needs to provide support for ATM, it also needs to differentiate between different classes of traffic supported by ATM, such as CBR, VBR and ABR. Bandwidth allocation represents an essential part of the MAC and controls the granting of requests at the headend. Finally, the contention resolution mechanism, which is the most important aspect of the MAC, consists of a backoff phase and retransmission phase.

5.4.6.6 Contention Resolution

A collision resolution algorithm needs to be implemented because request packets and possibly data packets are transmitted in a contention fashion. A wide variety of algorithms can be used. Because cable modems cannot monitor collisions, feedback information about contended requests is provided by the headend. The algorithm must also take fairness into account, such as compensating for the delay it receives through the feedback information. (See ranging procedure.)

Two mechanisms for contention resolution are described below:

1. Tree resolution and priority mechanism. Adopted by IEEE 802.14 for the ATM-centric cable modem
2. Binary exponential backoff. Adopted by MCNS/SCTE for the IP-based cable modem

Tree-based Contention Resolution Algorithm — The *n*-ary tree-based contention resolution algorithm was adopted for the ATM-centric modems. The principle behind it can best be described in terms of collision management, splitting the colliding entities into a smaller and more manageable subset, and building a hierarchy stack to throttle and control collision, classify the colliding entities, and compensate for the delay due to the HFC topology.

When a MAC entity (in cable modem) has data to send, it first must send the appropriate message requesting upstream bandwidth so it can be reserved by the headend. Since more than one entity is competing on this shared medium, collision will inevitably occur. A tree-based contention resolution algorithm is used to resolve this collision. The contention algorithm operates as follows: all the colliding entities will split into *n* subsets, and each of them randomly selects a number between 1 and *n*. This begins to form a hierarchy stack that will be managed by the headend in order to resolve the contention in an orderly and fair manner. The idea is to allow different subsets to retransmit first, while the subsets from 2 to *n* wait for their turn. In building this hierarchy, the QoS profile associated with the collided entity is classified further within that subset, forming yet another pecking order.

If there is another collision within a subset, then the first subset splits again, forming another subset, hence *n*-ary. The number of subgroups continues splitting further until the original collision is resolved. The subsets that are already waiting in the stack must have their positions shifted up in the stack accordingly so as to leave room for the new entities that collided. If no collision occurs, the entities with the lowest level in the hierarchy will get their opportunity to transmit, until all colliding entities are resolved.

The above algorithm works very well if one assumes that an entity received its collision feedback immediately. However this is not the case for HFC. Instead, the feedback is conveyed to the colliding entity via the next frame of the downstream frame. The tree-splitting algorithm is therefore modified further to accommodate this delay in feedback; that is, the level of the hierarchy stack is modified to accommodate the delay as well as the new collisions as the tree continues splitting.

There is a variety of mechanisms to limit entry of new packets to the system and thereby avoid congestion collapse. New requests (based on their admission priority) might be blocked during initial contention access to prevent excessive collisions. The admission control mechanism is based on pre-assigned priorities and is used to classify QoS in terms of contention access performance.

Or, new requests occupy different levels in the hierarchy based on their arrival time, or could send their requests on a first-come-first-served basis.

If the algorithm is blocking, the new requests are not allowed to use the slot reserved for collision resolution. Instead, they will be queued in the hierarchy of the stack and allowed to randomly select a slot among the remaining available slots.

IEEE 802.14 considered other allocation resolution algorithms such as the p-Persistence algorithm, an adaptation of a stabilized ALOHA protocol to frames with multiple contention slots. Newly active stations and stations resolving collisions have an equal probability of access p (p-persistence) to contention slot within a frame. p is determined by an estimate of the number of backlogged stations computed by the headend and sent to the station in the downstream frames.

After extensive simulation (performed by NIST and Georgia Institute of Technology), the tree-based blocking algorithm performance was found superior to the p-Persistence algorithm.

Another reason the contention resolution scheme was chosen for the ATM-centric modem is the probability density function of the access. Delay for a cable modem is computed, (the time a packet is generated until it is received at the headend). This measurement is considered especially important for issues related to Cell Delay Variation (CDV) in ATM environments.

Binary exponential back-off Contention Resolution — This contention resolution was adopted by MCNS/SCTE for the IP-based cable modem. The headend controls assignments on the upstream channel through feedback and determines which minislots are subject to collisions. This method of contention resolution is based on a truncated binary exponential back-off, with the headend controlling the initial and maximum back-off window.

When a cable modem enters the contention resolution process (due to collision), it sets its internal back-off window to the value conveyed that is in effect. The cable modem randomly selects a number within its back-off window. This random value indicates the number of contention transmit opportunities that the cable modem defers before transmitting.

After a contention transmission, if the request was not granted, the cable modem increases its back-off window by a factor of two, again randomly selects a number within its new back-off window, and repeats the deferring process. If the maximum number of retries is reached, then the PDU must be discarded.

5.4.7 Cable Modem Operation (Service Perspective)

We now provide a bird's eye view of what MSOs hope when they deploy cable modems.

5.4.7.1 Review of Cable Modem Operation

On power-up, the cable modem is in the unregistered mode. The PMD performs physical layer synchronization, followed by the TC, which performs synchronization as well as framing the information packet. The format for the upstream is MPEG, and a MiniPDU is created for it from timeslots controlled and programmed by the headend.

The cable modem then seeks and registers to join the network and exchanges security cookies and other parameters with the headend. Once ranged, a picture begins to emerge and operation commences. Mini PDUs can be concatenated to form an ATM cell for the ATM-centric modem, or IP packets for the IP-centric modem (as shown in Figure 5.11). Delineation of packets/ATM cells is performed with available HUNT state machine techniques.

When a cable modem needs to send PDUs and has no allocation pending, it requests an allocation by sending a request PDU in a MiniPDU. If the contention is successful, the headend will allocate the requested upstream in the grant information elements bandwidth and informs the cable modem, using the downstream. The cable modem may then send the PDUs in the allocated slots. If contention occurred, the cable modem invokes either tree resolution and priority mechanism (if ATM-based modem) or binary exponential back-off mechanism (if IP-based modem).

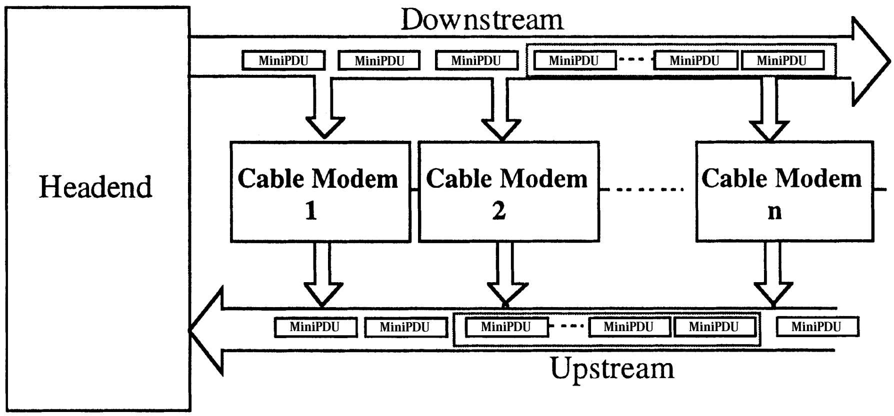

Figure 5.11 Cable modem operation

In the downstream direction, the cable modem receives a stream of ATM cells or PDU packets encapsulated over the MPEG packet. Management PDUs with an identifier address a particular cable modem that has only local significance. Each cable modem filters its incoming PDUs based on its identifier.

IP connectivity (to obtain an IP address) for the IP-based modem is invoked by the cable modem using the DHCP mechanism (RFC-1541).

5.4.7.2 Cable Modem Service Aspects

The MSOs have traditionally focused on quick returns to meet their short term business goal. MSOs attitude toward customer service is, admittedly, not good but they are becoming more receptive given the new dynamics of the market. The AT&T/TCI merger will set a new standard for the industry because AT&T has an excellent customer services reputation.

The key differentiated services cable operators are likely to provide are

- high-speed data services (Internet access)
- voice/video over IP
- broadcast, one-way entertainment
- telephony (wireline and wireless)
- digital NVOD
- work at home
- e-commerce/shopping

Convergence of these services across millions of U.S. households will change the way people live, work, and play. Byproducts of this convergence will be a major source of growth and opportunity for the U.S. economy.

The key differentiated market entries for MSOs are most likely to be

- time-to-market
- quality of service

Although time-to-market is important in the short term, it will not, however, be the ultimate deciding factor to win new customers, especially from the telephone companies. Time-to-market is important only if customer service and cost are satisfactorily met. Their competitors, the telephone operators, enjoy a very good customer service reputation, and that in itself will be a marketing tool they can use effectively to win cable customers. The telephone operators also have deep pockets to build a video infrastructure and to leverage the present infrastructure in billing, network management, and network reliability.

The battle for the MSOs to gain market share will not be easy, something of which the cable operators are very much aware.

GLOSSARY

Algorithm Well-defined rule or process for arriving at a solution to a problem. In networking, algorithms are commonly used to determine the best route for traffic from a particular source to a particular destination.

Amplifier A device that boosts the strength of an electronic signal. In a cable system, amplifiers are spaced at regular intervals throughout the system to keep signals picture-perfect regardless of the distance they must travel.

Asynchronous Transfer Mode (ATM) The transfer mode in which information is organized into cells; it is asynchronous in the sense that the recurrence of cells containing information from an individual user is not necessarily periodic.

ATM Cell A digital information block of fixed length (53 octets) identified by a label at the ATM layer.

Available Bit Rate (ABR) A service class that is an ATM layer service where the limiting ATM layer transfers characteristics provided by the network that may change subsequent to connection establishment.

Bandwidth A measurable characteristic defining the available resources of a device in a specific time period (typically in one second).

CATV (Community Antenna Television or Cable Television) A communication system that simultaneously distributes via a coaxial cable several different channels of broadcast programs and other information to customers.

Channel A communication path. Multiple channels can be multiplexed over a single cable in the cable television environment.

Coaxial cable Actual line of transmission for carrying television signals. Its principal conductor is either a pure copper or copper-coated wire, surrounded by insulation and then encased in aluminum.

Constant bit rate (CBR) A service class intended for real-time applications, i.e., those requiring tightly constrained delay and delay variation, as would be appropriate for voice and video applications. The consistent availability of a fixed quantity of bandwidth is considered appropriate for CBR service.

CRC Cyclic redundancy check. An error-checking technique in which the frame recipient calculates a remainder by dividing frame contents by a prime binary divisor and compares the calculated remainder to a value stored in the frame by the sending node.

Data link layer In Open System Interconnection (OSI) architecture, the layer that provides services to transfer data over the transmission link between open systems.

Delay The elapsed time between the instant when user information is submitted to the network and when it is received by the user at the other end.

Digital compression An engineering technique for converting a cable television signal to digital format in which it can easily be stored.

Downstream Flow of signals from the cable system headend through the distribution network to the customer.

End user A person, organization, or telecommunications system that accesses the network in order to communicate via the services it provides.

Feeder cable Coaxial cables that run along streets within the served area and connect between the individual taps which serve the customer drops.

Fiber node A point of interface between a fiber trunk and the coaxial distribution.

Fiber optics Very thin and pliable tubes of glass or plastic used to carry wide bands of frequencies.

Guardband Provides for slot timing uncertainty due to inaccuracy of the ranging.

Headend The central location, in an MSO environment, that has access to signals traveling in both the forward and reverse directions.

Header Protocol control information located at the beginning of a protocol data unit.

High split A frequency division scheme that allows bidirectional traffic on a single cable. Reverse path signals propagate to the headend from 5 to 174 MHz. Forward path signals go from the headend from 234 MHz to the upper frequency limit. A guardband is located in 174 to 234 MHz.

Home passed Total number of homes which have the potential for being connected to the cable system.

Internet Term used to refer to the largest global internetwork, connecting tens of thousands of networks worldwide and having a culture that focuses on research and standardization based on real-life use. Many leading edge network technologies come from the Internet community. The Internet evolved in part from ARPANET. At one time, it was called the DARPA Internet. Not to be confused with the general term *internet*.

IP Internet Protocol. Network layer protocol in the TCP/IP stack offering a connectionless internetwork service. IP provides features for addressing, type-of-service specification, fragmentation and reassemble, and security. Documented in RFC 791.

IP over ATM Specification for running IP over ATM in a manner that takes full advantage of the features of ATM. Defined in RFC 1577. Sometimes called CIA.

ISO International Organization for Standardization. International organization that is responsible for a wide range of standards, including those relevant to networking. ISO developed the OSI reference model, a popular networking reference model.

Layer A subdivision of the Open System Interconnection (OSI) architecture, constituted by subsystems of the same rank.

LLC Logical Link Control. Higher of the two data link layer sublayers defined by the IEEE. The LLC sublayer handles error control, flow control, framing, and MAC-sublayer addressing. The most prevalent LLC protocol is IEEE 802.2, which includes both connectionless and connection-oriented variants.

Medium access control (MAC) address An address that identifies a particular medium access control (MAC) sublayer service-access point.

Medium access control (MAC) procedure In a subnetwork, that part of the protocol that governs access to the transmission medium independent of the physical characteristics of the medium, but takes into account the topological aspects of the subnetworks, in order to enable the exchange of data between nodes. MAC procedures include framing and error protection.

Medium access control (MAC) sublayer Part of the data link layer that supports topology-dependent functions and uses the services of the physical layer to provide services to the logical link control (LLC) sublayer.

Mid split A frequency division scheme that allows bidirectional traffic on a single cable. Reverse channel signals propagate to the headend from 5 to 108 MHz. Forward path signals go from the headend from 162 MHz to the upper frequency limit. The guardband is located in 108 to 162 MHz.

Mini-slot An integer multiple of 6.25 μsec increments. It represents the byte-time needed for transmission off a fixed number of bytes.

MCNS Multimedia cable network system. A consortium of Comcast Cable Communications, Inc., Cox Communications, Tele-Communications, Inc., and Time Warner Cable, interested in deploying high-speed data communications systems on cable television systems.

MSO Multiple System Operators. Company that owns and operates more than one cable television system.

NTSC National Television Systems Committee. Committee that defined the analog color television broadcast standard used today in North America.

Network Collection of computers, printers, routers, switches, and other devices that are able to communicate with each other over some transmission medium.

NIC Network interface card. Board that provides network communication capabilities to and from a computer system.

Payload Portion of a frame that contains upper-layer information (data).

Physical layer In Open System Interconnections (OSI) architecture, the layer that provides services to transmit bits or groups of bits over a transmission link between open systems.

Protocol A set of rules and formats that determines the communication behavior of layer entities in the performance of the layer functions.

QAM Quadrature amplitude modulation. A method of modulating digital signals onto a radio-frequency carrier signal involving both amplitude and phase coding.

QPSK Quadrature phase-shift keying. A method of modulating digital signals onto a radio-frequency carrier signal using four phase states to code two digital bits.

QoS Quality of service. The accumulation of the cell loss, delay, and delay variation incurred by those cells belonging to a particular ATM connection.

SAR Segmentation and reassemble. One of the two sublayers of the AAL CPCS, responsible for dividing (at the source) and reassembling (at the destination) the PDUs passed from the CS. The SAR sublayer takes the PDUs processed by the CS and, after dividing them into 48-byte pieces of payload data, passes them to the ATM layer for further processing.

Scrambling A signal security technique for rendering a TV picture unviewable, while permitting full restoration with a properly authorized decoder or descrambler.

Sublayer A subdivision of a layer in the Open System Interconnection (OSI) reference model.

Subnetwork Subnetworks are physically formed by connecting adjacent nodes with transmission links.

Subsplit A frequency division scheme that allows bidirectional traffic on a single cable. Reverse path signals come to the headend from 5 to 30 (up to 42 on newer systems) MHz. Forward path signals go from the headend from 54 MHz to the upper frequency limit.

Synchronization Establishment of common timing between sender and receiver.

TCP Transmission Control Protocol. Connection-oriented transport layer protocol that provides reliable full-duplex data transmission. TCP is part of the TCP/IP protocol stack. See also TCP/IP.

TCP/IP Transmission Control Protocol/Internet Protocol. Common name for the suite of protocols developed by the U.S. DOD in the seventies to support the construction of worldwide internetworks. TCP and IP are the two best known protocols in the suite. See also IP and TCP.

TDM Time-division multiplexing. Technique in which information from multiple channels can be allocated bandwidth on a single wire, based on preassigned time slots. Bandwidth is allocated to each channel regardless of whether the station has data to transmit. Compare with ATDM, FDM, and statistical multiplexing.

Topology Physical arrangement of network nodes and media within an enterprise networking structure.

Transmission Medium The material on which information signals may be carried; e.g., optical fiber, coaxial cable, and twisted-wire pairs.

Upstream Flow of any information from the customer, through the cable system, to the headend.

WWW World Wide Web. Large network of Internet servers providing hypertext and other services to terminals running client applications such as a WWW browser.

WWW browser Client application, such as Mosaic, used to access hypertext documents and other services located on innumerable remote servers throughout the WWW and Internet. See also Internet and WWW.

10BaseT 10-Mbps baseband Ethernet specification using two pairs of twisted-pair cabling (Category 3, 4, or 5): one pair for transmitting data and the other for receiving data. 10BaseT, which is part of the IEEE 802.3 specification, has a distance limit of approximately 100 meters per segment.

ACRONYMS

AAL	ATM adaptation layer
ABR	Available bit rate
ADSL	Asymmetric digital subscriber line
ANM	Answer message
ANSI	American National Standards Institute
ATM	Asynchronous transfer mode
BER	Bit error rate
BW	Bandwidth
CATV	Community antenna television
CBR	Constant bit rate
CDMA	Code division multiple access
CPE	Customer premises equipment
CRC	Cyclic redundancy check
CSMA/CD	Carrier sense multiple access with collision detection
HE	Headend
HEC	Header error control
HFC	Hybrid fiber coax
IEEE	Institute of Electrical and Electronics Engineers
ITU	International Telecommunication Union

IP	Internet Protocol
LLC	Logical link control
MAC	Medium access control
MPEGx	Motion Picture Editor's Group compression algorithm x
OSI	Open system interconnect
PMD	Physical medium dependent
QAM	Quadrature amplitude modulation
QPSK	Quaternary phase shift keying
QOS	Quality of service
RF	Radio frequency
SAAL	Signaling ATM adaptation layer
TDMA	Time division multiple access
VBR	Variable bit rate

REFERENCES

1. ANSI/IEEE. "Carrier Sense Multiple Access with Collision Detection (CSMA/CD) Access Method and Physical Layer Specifications." ANSI/IEEE Std. 802.3-1985, 1985.
2. Azzam, A. and Brandt, M., Dajer, M., Eng, J., Lin, D., Mollenauer, J., Siller, C., Grobicki, C., Sriram, K., Ulm, J. "IEEE P 802.14 Cable-TV Functional Requirements and Evaluation Criteria." November 1993.
3. Azzam, A. et al. "ATM over ADSL" ATM Forum Magazine (53 Byte), 1997.
4. Bingham, J. and Jacobson, K. "A proposal for an MAC protocol to support both QPSK and SDMT." IEEE 802.14-95/137.
5. Currivan, B. "CATV Upstream Channel Model, Rev 1.0." IEEE 802.14-95/133, March 1997.
6. "Data-Over-Cable Service Interface Specifications Radio Frequency Interface Specification." SP-RFI-I02-971008 (Interim Specification). 1997.
7. De Prycker, M. "Asynchronous Transfer Mode Solution for B-ISDN." 1993.
8. Gingold, D. "Integrated Digital Services for Cable: Economics, Architecture, and the Role of Standards — MIT Research Program on Communications Policy." IEEE 802.14-96/230. September 1996.
9. Golmie, N. "Performance Evaluation of Contention Resolution Algorithms: Ternary-tree vs. p-Persistence." IEEE 802.14/96-241. September 1996.
10. Golmie N. "Performance Evaluation of MAC Protocol Components for HFC Networks." Broadband Access Systems, Proc. SPIE 2917, pp.120-130. Boston, Massachusetts. November 1996.
11. Grossman, D. "Security overview." IEEE 802.14-97/030. March 1997.
12. Hilton, R. and Prodan, R. "Evolving Cable Network Architecture Cable Televisions Laboratory." ATM Forum/95-0075. February 1995.
13. Karaoguz, J. Gottfried Ungerboeck. "Formal Proposal: Frequency Agile Multi-Mode (FAMM) Single-Carrier Modems for Upstream Transmission in HFC Systems." IEEE 802.14-95/131. November 7, 1995.
14. "Cable-TV access method and physical layer specification." IEEE Project 802.14/a Draft 3 Revision 1. March 1998.
15. "Information technology — generic coding of moving pictures and associated audio information systems." ITU-T Recommendation H.222.0 (1995) | ISO/IEC 13818-1:1996.

16. “Digital multi-programme systems for television sound and data services for cable distribution.” ITU-T Recommendation J.83 October 1995.
17. “Information technology — Open Systems Interconnection — Local area networks — Medium Access Control (MAC) service definition.” ISO/IEC10039 ISO/IEC 10039:1991.
18. Kwok, T. “Communications Requirements of Multimedia Applications: A preliminary study.” International Conference on Selected Topics in Wireless Communications, Vancouver, Canada. 1992.
19. Laubach, M. “ATM HFC Overview.” IEEE 802.14-95/022. March 1995.
20. ________. “MAC <> Phy-TC Sublayer interface.” IEEE 802.14-97/025. January 1997.
21. Limb, J. “Performance Evaluation Process for MAC Protocols.” IEEE 802.14-96/83R2. May 1996.
22. Prodan, R. “Letter From CableLabs - regarding Annex A/B.” IEEE 802.14-96/205. July 1996.
23. Quinn, S. “Requirements on HFC Access Networks — A Public Network Operator’s Perspective.” IEEE 802.14-95/099. September 1995.
24. Sriram, P. “ADAPt MAC PDU and MAC-PHY Services in Support of ATM.” IEEE 802.14-95/168. November 1995.
25. Van der Plas, G. “APON: An ATM-based FITL System.” EFOC&N’93, 1993.
26. Vandenameele, J. “How to upgrade CATV networks to provide interactive ATM-based services.” GLOBECOM 95. Singapore, November 1995.
27. Verbiest, W. “Integrated Broadband Access.” Proc. Fourth IEEE conference on Telecommunication, Manchester 1993.