RC 20568 (90765) 7/1/1996
Computer Science/Mathematics 20 pages

IBM Research Report

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Abstract: Current efforts for digital data transmission over hybrid fiber-coaxial (HFC) networks will provide an efficient data transport mechanism in the "last mile" to residential users and will enable a very large number of services to the home. Provision of these services requires a complete end-to-end network architecture that provides an efficient connection between the server and the end-user. Thus, it is necessary for the currently isolated HFC islands to gradually evolve into an efficient, highly connected, high-speed network.

In this paper, we review HFC networks and establish that they provide a more attractive and promising solution than the alternatives for "last mile" connectivity to the home, such as telephone connections. We present a list of broadband services that are possible due to the high-speed data capabilities of HFC networks and describe the necessary end-to-end infrastructure to support these applications as well as possible evolution and migration paths for developing these end-to-end network architectures.

1 Introduction

Some of the most popular "techno-buzzwords" heard on a daily basis and repeated over-and-over by industry analysts, news reporters, a myriad of computer savvy youngsters, etc, have to do with the *Web* and the *information superhighway*, or the more catchy *Infobahn*. The Web, of course, refers to the collection of millions of computers connected through the world-wide computer network, called the *Internet*, and is accessible through appealing *multimedia graphics user interfaces*, called *Web browsers*. The Web and the Web browsers have brought the riches of the digital world to people's desktops at the touch of a button, while the Infobahn is the means over which the digital information travels on the Web. The great effort undertaken to provide on- and off-ramps to the Infobahn is underscored by the numerous publications in the area [4,5,6,7,8]. In this paper, we will present what is needed for high-speed data connectivity to the home using cable TV technology, and how this will further enhance our experience of the digital world.

Currently, residential customers with on-line access enjoy services ranging from *electronic-mail*, to *airline-booking*, to *electronic banking*, to *update summaries* of the latest news, stock prices, weather conditions, etc. Most of these services are simple text-oriented services that do not pose a major burden on the network infrastructure and customer terminal equipment, e.g., voice-grade modems, although they may still overburden underpowered servers.

Historically, the most popular on-line service and Internet application was the text-oriented *e-mail*, either in the form of person-to-person communication, or in the form of special interest discussion groups. Yet, with the ever-increasing expansion of the Internet and in particular its multimedia instantiation, the Web, and the ever-increasing sophistication of personal computers, more and more elaborate data services and applications are being developed. There is a desire for enhanced versions of the current text-oriented applications, as well as an increased appetite for brand new applications like *Web surfing*, which is both an educational and entertaining experience, *remote learning* and *education*, delivering multimedia educational content to end-users, *electronic commerce* and *virtual malls*, where people will shop on-line, and *telecommuting* and *home office* applications, where users will work at home as productively as if they were at the workplace.

All of these new services are graphics-, audio-, and video-oriented, and contrary to the simple text-oriented "first-generation" applications, they demand a high-speed communications infrastructure. Moreover, the requirement for "real-time" interactivity, i.e., for sub-second system response times, makes the need for multi-Mbps high-speed communications even greater.

Large corporations and academic institutions have the benefit of scale and they can obtain, at a reasonable cost, high-speed connectivity to the Internet and other data services via high-speed LANs, MANs, and WANs. For small- and medium-sized businesses, high-speed communications is hardly even an option, while for residential customers it is practically non-existent. For them, the only viable solution for data communications is the *voice-grade* (telephone line) *modems* that currently can support no more than 28.8 Kbps data speeds, in full duplex mode – more expensive 33.6 Kbps modems are just entering the market. Although this speed may be sufficient for e-mail, it is clearly inadequate for any real-time application that involves media other than plain text. An average Web page with text only is about 2 KBytes long, which has a transmission delay of approximately 0.6 sec at the "fast" voice-grade modem rate of 28.8 Kbps. The addition of the simplest icons or graphics to such a Web page increases its size to several tens of KBytes requiring several seconds to be transmitted. Taking into consideration that Web searching usually takes a user through several "intermediate" Web pages, it is clear that even a simple activity like Web surfing can hardly be a thrilling experience using voice-grade modems.

No wonder then, that service providers and customers are urging the communications community to come up with newer, faster, and cheaper alternatives for providing high-speed communications to the millions of residential and small business customers. Currently, there are three possible transport means that can be used to bring high-speed connectivity to customers: (a) digital telephone-lines; (b) cable TV systems; (c) aerial transmission systems. The first alternative takes advantage of the existing point-to-point telephone service, while the other two take advantage of broadcast systems for distributing TV programming.

Highly sophisticated interactive broadband services require the use of a *return path*, or *upstream channel*, for transmissions from a customer site. Of the three alternatives, the aerial transmission systems can be, currently, used only in a *hybrid mode* where the return path is based on the use of a voice-grade modem. Hence, this solution can only be temporary and addresses only a limited spectrum of broadband applications, due to the limitations of the return path, and the added complexity in system operation, since the high-speed service provider would have to use, manage and associate data streams that are concurrently transported over different media.

Among the remaining two alternatives, digital telephone service has been evolving for over a decade. The most widely available offering, in relative terms, is the *Integrated Services Digital Network* (ISDN) basic rate service that can provide up to 128 Kbps over currently deployed unshielded twisted-pair (UTP) copper cabling. Technical and logistics problems prevented this service from becoming as widespread as originally hoped for. Even if these problems are resolved, 128 Kbps are no longer sufficient for a full range of broadband services.

Thus, telephone operators are testing new asymmetric communication technologies that will allow for hundreds of Kbps transmission speeds on the return path, and several Mbps speeds on the *forward path*, or *downstream channel*. Yet, we do not envision that these solutions will be mass-marketed to residential customers any time soon. The technology has not yet sufficiently matured and the equipment is still too expensive to be affordable to residential customers.

As cable TV (CaTV) operators pursue their quest to increase their revenues, they have found that their CaTV plants can provide unsurpassed aggregate bandwidth that can be used for very high-speed data communications. Hence, for the last few years, as part of their system maintenance and upgrade, they have started provisioning their infrastructure for two-way communications. Today about 25% of the CaTV systems in the US, where CaTV passes over 90% of the residences, is two-way capable, and the rate of upgrading is rapidly increasing. Two-way-communications-capable CaTV systems will provide speeds of several tens of Mbps on the downstream and several Mbps on the upstream. At such high speeds, CaTV systems will be the only systems that can provide a full range of broadband services in an integrated manner to *residential* customers for the foreseeable future.

With the possibility of high-speed access to residences, the expectation rises that the CaTV data capability, or for that matter even digital telephone data capability, will immediately activate all the desired broadband services, such as the ones mentioned previously, to the home. As we argue later in the paper, this will not be possible overnight. The high-speed connectivity to the home is merely an *enabling* technology. It is a high-speed communications solution that governs only the *last-mile* distribution network, sometimes referred to as the *access network*. Bringing a sophisticated broadband application to the home requires an end-to-end solution, one that includes the service provider and his equipment, the totality of intermediate communication networks and their capabilities, the access network, and finally the customer home equipment.

This paper is organized as follows. In the following section, we provide a short overview and a comparison of the CaTV-based and telephony-based last-mile access networks. In Section 3, we present the spectrum of applications enabled by the high-speed CaTV network environment and provide a comprehensive classification based on the network characteristics. In Section 4, we describe the requirements for an end-to-end broadband service, and argue that, in addition to the access network, several additional elements are required to implement complete end-to-end services. We discuss the current situation and describe a migration path towards getting the desired services, i.e., the route that CaTV operators have to follow in order to provide and guarantee the whole range of broadband services that CaTV can enable.

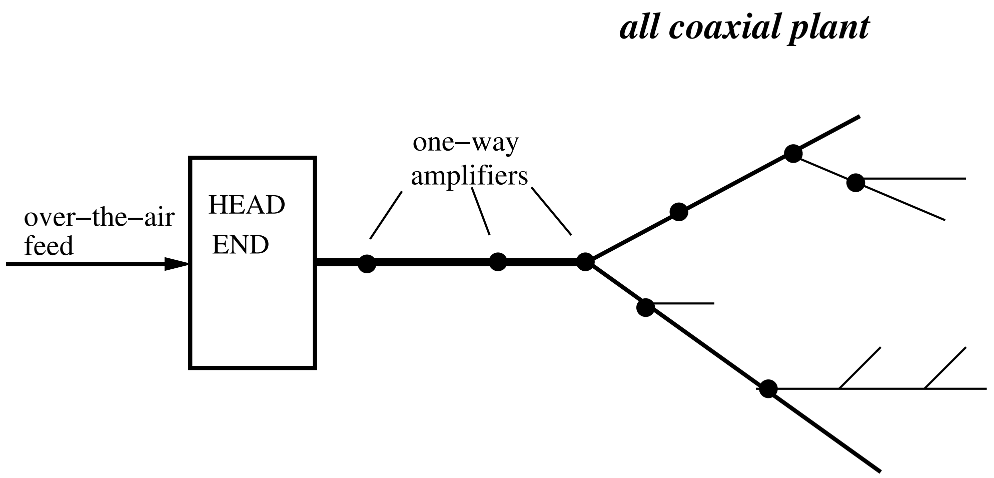

Figure 1: A coaxial CaTV network

2 The Last-Mile Access Networks

Customers are not directly connected to high-speed *backbone* networks, but rather, they are connected to "local" access networks, which are then connected to regional networks, which are then connected to national backbone networks. This hierarchical structure allows for better management of the overall communication network, and decreases its operating cost. Current telephone access networks have a low data speed capacity, e.g., 28.8 Kbps. Hence, they present an obstacle in delivering high-bandwidth broadband services to customers.

In order to remove this obstacle, better and more efficient access networks and technologies need to be introduced. In this section, we will describe two such alternatives, one based on the CaTV distribution network, which is the main focus of this paper, and one based on the introduction of digital telephone lines.

2.1 The CaTV Distribution Network

Cable TV was first introduced in the late '40s for distributing over-the-air TV broadcasts to (cable) subscribers that were located too far from TV stations to receive their transmissions with regular TV antennas. For that reason, CaTV, or better CATV, used to stand for *Community Aerial TV*. With the passage of time, CaTV penetrated several residential neighborhoods that did not necessarily have any problem in receiving regular programs over the air. In these neighborhoods, CaTV brought better quality of picture, and more importantly wider selection of TV channels, some of them not even available over the air. Approximately $60 - 70$ channels can be carried by conventional (analog) CaTV plants.

Historically, CaTV networks were developed as one-way broadcast systems using the network topology best suited for this service, the tree topology shown in Figure 1. The system consists of a *head-end* (H/E) station, that collects the TV programs, usually through satellite down-links, and then distributes them over coaxial cables along the branches of a tree-like network to customer sites, which are located at the leaves of the tree. The distance between the H/E and a remote customer can be several tens of kilometers. Hence, to compensate for signal attenuation and maintain a good signal quality, there are several one-way analog amplifiers along the cable, as many as 30, from the H/E to a customer.

To increase system capacity, reliability, picture quality, and resistance to noise interference, and to decrease maintenance costs, during the last few years and with an ever-increasing rate, CaTV operators are replacing large sections of their all-coaxial plans with fiber. The resulting network is called, appropriately, a *hybrid fiber-coaxial* (HFC) network.

2.1.1 The CaTV HFC Access Network

In an HFC network, the main "tree-trunk" from the H/E to the outskirts of a community, spanning on the order of a thousand homes, is replaced with high-reliability, low-attenuation fiber. This implies that a large number of the analog amplifiers along the long tree-trunk are not needed any more. Hence, the reliability of the system increases and the quality of the signal improves, since there exist fewer active components between the origin (H/E) and the destination (customer site) of the TV signal.

With the introduction of a "cleaner", more efficient communication path, also comes the potential for providing two-way data services over the HFC network. In order to provide these services, CaTV operators need not only to upgrade their networks to HFC, but to replace their one-way amplifiers with two-way amplifiers, to allow upstream transmissions from a customer to the H/E. Although this can happen during the installation of the fiber for those amplifiers located on it, it may take some extra time to replace the ones located within the customer coaxial neighborhood. Figure 2 shows a two-way capable HFC network. The *fiber nodes* at the boundaries of the fiber and coaxial plant regions convert light to electrical signals for *downstream* transmissions, i.e., from the H/E to subscribers, and vice versa for the *upstream* transmissions.

Of the bandwidth available today on an HFC network (750 MHz today, 1 GHz in future systems), the range between 5 MHz and 42 MHz will be used for upstream transmissions, with the range of 54 MHz and above for downstream transmissions. To guarantee compatibility with current systems, the frequency spectrum between 54 MHz and 450 MHz will remain undisturbed to carry current analog and digital transmissions, while the frequencies above

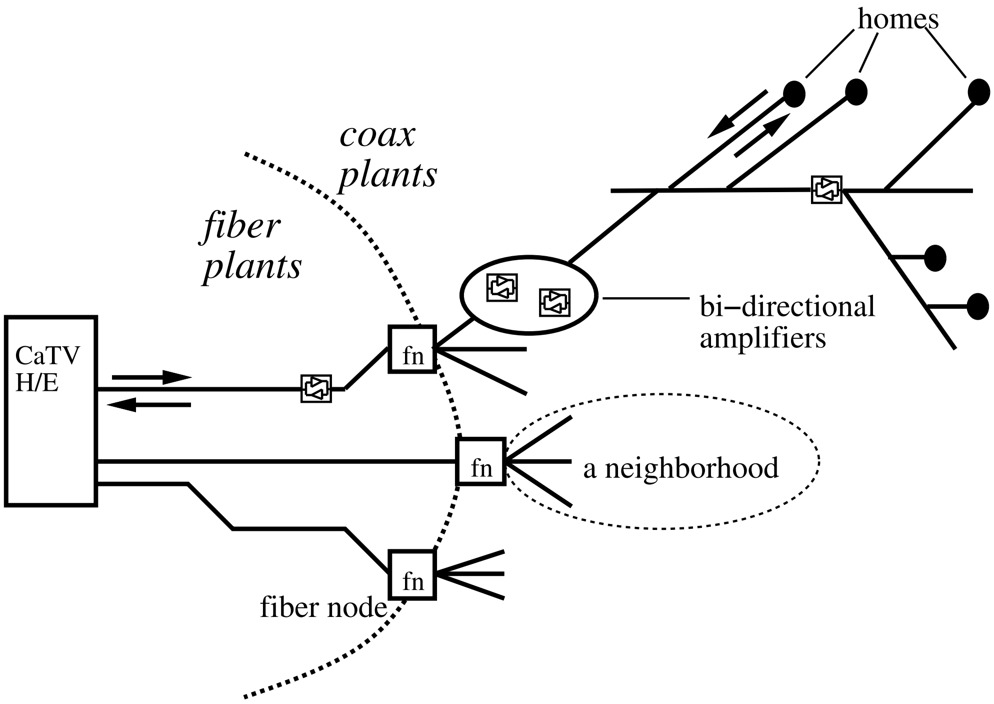

Figure 2: A two-way capable CaTV HFC network

450 MHz will be used to provide enhanced switched or broadcast data services. These frequency allocations are illustrated in Figure 3.

Both the upstream and downstream spectra will not be available all at once for transmission or reception. Instead, per IEEE 802.14 [10], the upstream spectrum will be divided into channels from a few hundred KHz to approximately 1 MHz wide, while the downstream will be divided into 6 MHz channels. With appropriate modulation techniques, transmission rates of about $2-3$ Mbps are possible per upstream channel, using QPSK modulation, while

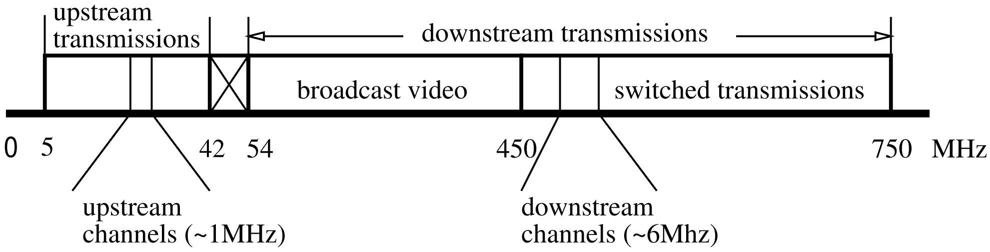

Figure 3: Upstream and downstream transmission regions in a 2-way HFC network

transmission rates of about 30 Mbps are possible per downstream channel, using 64-QAM modulation. Also, higher speeds are achievable with more advanced modulation techniques.

Similar to the need for a voice-grade modem for data transmissions over regular telephone lines, one needs to use a *cable modem* to transmit and receive digital data over an HFC network. Underscoring the ever-increasing desire for HFC-based data services, a recent industry study projects an explosive increase of the cable modem market at about 100% or more growth per year for the next few years [3].

In order to achieve the widespread acceptance enjoyed by voice-grade modems, cable modems and the HFC networks on which they operate must be standardized. In other words, the communication protocols that govern the modulation techniques, the transmission rates, the sharing of the HFC network resources, the management of the network, etc, must be well defined so that third-party cable modem manufacturers can build them and be assured that the modems will operate on any (standard compliant) two-way HFC network. Standardization will lower the cost of cable modems to the consumers, but most importantly will guarantee interoperability of the modems purchased from one's local electronics store. It would be extremely annoying, to say the least, if consumers have to buy new cable modems every time they move into new residences that are served by a different cable operator.

The IEEE 802.14 working group (WG) is working towards the development of *physical* (PHY) and *medium access* (MAC) layer communication protocols for HFC networks [9,10].[1] It is expected that the first draft of the IEEE 802.14 standard will be available before the end of this year, with the basic standardization process being completed during the first half of 1997.

2.2 The Digital Subscriber Line Access Network

The only truly currently available means for two-way communication to the home is via the analog *plain old telephone service* (POTS). Its main advantage is that it is practically globally available, allowing anybody with a voice-grade modem to (theoretically) exchange digital data with any other voice-grade modem in the world. POTS systems, though, provide low-bandwidth connections, currently up to 28.8 Kbps, and theoretically no more than 34 Kbps.

It is possible to provide higher transmission speeds over copper telephone lines by removing the 4 KHz bandwidth restriction historically imposed to facilitate analog voice communications. Telephone operators have been pursuing this direction for the last few years through the introduction of various *digital subscriber line* (DSL) solutions which allow digital data transmission to/from the customer terminal equipment (telephones, computers, etc).

[1] The IEEE 802.14 WG maintains a Web page at URL "*http://www.walkingdog.com/catv.html.*"

The most known and available DSL solution is the *ISDN* service, which can transmit digital data over UTP telephone wires on two 64 Kbps channels, called the B channels, and one 16 Kbps signaling channel, called the D channel, in full duplex mode. The two B channels can be used independently for voice and/or data transmission or can be combined into a single 128 Kbps data channel.

ISDN offerings are over a decade old, and they were initially available to a limited number of businesses. Lately, many local exchange carriers have started providing ISDN services to residential customers as well. Despite its apparent superiority over analog data connections, ISDN is not as widespread as expected, due to several technical and logistical problems. A significant problem is that ISDN cannot coexist on the same wires with analog POTS: one needs separate lines for ISDN and POTS to provide a "live" POTS service in case of power failure. This may lead to installation of additional telephone lines in homes; this, in conjuction with the limited number of technicians and customer service representatives aware of ISDN installations, may lead to a long delay to obtain the service after one requests for it. Furthermore, the customer needs to serve as his/her own system integrator and properly configure the connection between his/her computer, the ISDN modem, and the ISDN jack on the wall. Another problem is the cost: an ISDN modem may cost anywhere between $300 and $500 [11], well above the cost of regular analog line modems. Pricing policies are an additional problem, since they are regulated by government directives. At its simplest form, is an ISDN connection equivalent to one or two analog connections? Currently, different telephone operators use different charging philosophies. In a more complicated form, are the charges going to be the same as telephone charges, or not?

A significant impediment in the successful deployment of ISDN is its characteristic that it is an end-to-end solution, i.e., to benefit from ISDN, both communicating parties and the network in-between must support ISDN[2]. ISDN support by the network is not as widespread as desired, because upgrading the whole system to support ISDN connections over the long periods of time that a customer may want to remain connected, e.g. to an on-line data service or to his office computer, is extremely expensive to the telephone operator. The telephone system today has been designed around the 3 minute telephone call length. Data service connections can easily run for several hours, thus putting major stress on the telephone equipment.

Because of the problem mentioned, ISDN services are currently provided only to a small number of customers, although this number constantly increases. Moreover, the availability of multimedia applications and digitized video that require bandwidth in the order of Mbps,

[2]Moreover, the two parties must comply to the same standards; e.g., voice analog-to-digital (A/D) encoding in North America is different from the one in Europe!

suggests that ISDN speeds will not be sufficient for high-speed broadband services to the home.

To address this problem, a new generation of DSLs is being developed, called the *asymmetric DSL* (ADSL). Depending on the distance of a customer from the telephone center, speeds from approximately 1.5 Mbps (with a line length of 540 meters) to approximately 9 Mbps (with a line length of 270 meters) are possible for "downstream" transmissions, and 16 Kbps to 640 Kbps for "upstream" transmissions. Importantly, ADSL service can coexist with POTS on the same wires with POTS service available even when the ADSL modem does not operate. Due to these characteristics, ADSL is a promising high-speed telephone solution, but, it is still an immature and expensive technology; ADSL equipment is quite expensive, with ADSL modems costing at least $1,000 each [2]. In addition, the charging policies are still an open issue.

Even higher speeds are possible with very high-speed ADSL (VDSL), but like ADSL, this is still a technology under development that cannot easily be marketed to residential users any time soon.

For an excellent overview of DSL technologies, see [1].

2.3 Remarks

We believe that HFC-based services will cost less than corresponding services provided over telephone connections. This is because CaTV technology is naturally a shared medium technology, implying that equipment at the H/E can be more efficiently used by customers. The tree-and-branch topology of the CaTV system allows for the aggregation of all the traffic generated by and directed to its customers, who then can benefit from the same economy of scale that large institutions have long enjoyed when it comes to data networking.

On the other hand, telephone connections are point-to-point, which requires equipment to be practically dedicated to each subscriber. This increases the cost and complexity of providing high-speed services to large communities of residential customers. A case study has shown that the shared resources approach of CaTV results in tremendous cost savings over point-to-point ISDN connections per normalized peak bandwidth [12].

Moreover, with the HFC shared medium approach, it is possible to be continuously on-line, 24 hours a day, 7 days a week, without wasting any network resources, except during periods that one actively receives or transmits information over the network. With dial-up telephone connections, this cannot be easily done. It will be too costly for a customer to be continuously on-line, and it will be too costly for the telephone operators to engineer the network to operate over such long connection times per subscriber.

Also, the HFC technology can be gracefully upgraded to provide even higher bandwidth *per* customer without requiring any change in the customer's equipment. This can be done by placing the fiber nodes closer and closer to residences, giving rise to *fiber-to-the-neighborhood* and *fiber-to-the-curb* architectures. Communities as small as 10-20 homes can thus be serviced from each individual fiber node.

Based on the above, we believe that although data services to residential customers will be available via telephone connections, we do not believe that they will represent the bulk of digital transport mechanisms for many years to come. Due to lower data speeds achievable on them, logistic constraints and regulatory obstacles, any data offerings over telephone lines appear to be temporary solutions, only to be surpassed by CaTV offerings, at least in regions that CaTV has penetrated.

3 Applications

It has become clear that HFC networks with support for digital data transmission provide the only competitive alternative to telephone networks for communication to the home. Hybrid solutions for the down-link using, for example, over-the-air transmissions, such as satellite, microwave, etc, will soon experience bottlenecks due to the limited voice-grade telephone connections for the return path.

The main characteristic of HFC networks, which differentiates and makes them more attractive than the alternatives, is their ability to provide full-duplex connections with higher bandwidth to the home (end-user). As such, they can provide improved services to the end-user; especially in comparison with telephone networks, they provide advantages due to their broadcast nature as well.

The network infrastructure, such as the cable network, is only one of the significant elements necessary to provide an end-to-end service. There are other requirements as well such as powerful servers, management systems, etc. In the following, we describe several applications that are enabled by HFC networks, assuming that all the remaining service elements are in place. Such applications can be classified in several ways. We consider the more significant parameters of cable networks for a comprehensive classification: 1. the existence of 3 different streams: one digital upstream and two downstream, one for digital and one for analog transmission;
2. the broadcast nature of the transmission medium.
These characteristics enable a wide spectrum of applications ranging from traditional and conventional television services to interactive multimedia applications. Sophisticated interactive applications can be realized due to the ability to transmit audio and video digitally

Upstream	**Downstream**			
	Digital			*Analog*
(Digital)	*Data*	*Audio*	*Video*	*Video*
Data	Internet E-mail DoD Software download Multi-party games (Real-time)	AoD (Real-time) Music download Audio preview	VoD (Real-time) Near VoD (Real-time) Video download Video preview	Pay-Per-View Time-based subscription
Audio		Telephone Voice mail	Asymmetric conferencing	
Video		Asymmetric conferencing	Video conferencing Video mail	
No Upstream	Data subscription Data broadcast TV schedule Video-game download	Audio subscription (Real-time) radio station Audio broadcast	Video subscription (Real-time) Video broadcast	Subscription Broadcast

Table 1: The applications spectrum

DoD: *Data-on-Demand*; AoD: *Audio-on-Demand*; VoD: *Video-on-Demand*

in addition to data. Furthermore, in our classification we take into account the real-time or non-real-time nature of an application.

The classification of the most popular (expected) applications enabled in an HFC environment is shown in Table 1, where the rows of the table correspond to all possible media (data, audio and video) transmitted over the digital upstream connections, while the columns represent all possible media downstream transmissions in either digital or analog form. Each cell in the table represents a class of applications which combine the corresponding upstream and downstream transmissions; e.g., the entry with data upstream transmission and analog downstream transmission corresponds to applications where the client transmits data to the H/E, e.g., a movie request, and the H/E transmits the movie on one of the analog channels, as for example, in a pay-per-view application.

Clearly, each class can include several applications, which can be classified in categories using the two remaining parameters: *broadcasting* and *real-time transmission.* Based on these criteria, four different categories of applications emerge based on the broadcasting (or non-broadcasting) and real-time (or non-real-time) nature of the application. As the table indicates, there exist classes, and categories within classes, where no meaningful applications exist (or, at least, are not currently foreseeable).

3.1 Non-Real-Time Applications

A large set of non-real-time applications can be realized over HFC networks. Assuming a data upstream connection from the user to the H/E, for example, one can envision applications where various media are delivered to the end-user through the downstream connection.

A full-duplex digital data communication between the user and the H/E, allows access to all resources available through the global network. Internet access is probably the most important application; the user can access all available resources on the Internet, and use its services. This, in addition to access to other networks, will enable end-users to request data on demand, ranging from browsing shopping catalogs and theater schedules to news and weather forecast to banking. Currently, this class of applications is the most expected, because it will capitalize on a vast amount of already available information content. Examples of this application class include the following. *Remote education*, which basically consists of tapping into the vast resources available on digital libraries around the world that contain multimedia information and tutorial presentations on a vast array of topics. The popular *Web surfing* can be considered as a form of remote learning, if there exists a particular educational objective for the search, or a form of entertainment otherwise. *Home office*, where a person's office is their own home, and business is conducted entirely from home, and connection to clients is made through telephones and computers. *Electronic commerce*, which represents a vast array of monetary and, in general, financial transactions that can take place electronically via interconnected computers. The *virtual mall* and *remote shopping* are simple examples of electronic commerce, where people can (Web) browse through the pages of electronic-mail catalogs, request additional information for selected items and purchase them on-line. Clearly, in parallel to interactive applications, a non-interactive version of them will also be available, where users will request and download data on demand for consequent browsing, study, or use: catalogs, news, books, announcements, software delivery, catalog ordering, etc.

In addition to the above applications, Internet access also provides a significantly strong enabling technology for *telecommuting*, where users can tap into their office computer resources using a high-speed connection from home (significantly higher than what is conventionally available), and thus be as productive as in the office environment, but from the comfort of their home. Considering also the emerging policies against massive commuting for several categories of workers, this technology may become a significant factor for this trend to become more widely acceptable and successful.

Traditional *e-mail services* will further provide a significant improvement in interpersonal communication, allowing users to exchange text messages at a significantly lower cost than current voice connections. Clearly, these applications will be useful for business as well as non-business purposes.

Downstream delivery of digitized audio and/or video enables another popular category of applications. It becomes feasible to deliver to users non-real-time audio or video on-demand to their systems for later playback. In this fashion, users can initiate playback sessions at their leisure for speeches, music, video/audio previews, etc. Importantly, this class of applications can be used for mail services as well, where users will be able to exchange audio (voice) and/or video mail messages.

Audio or video information in the digital upstream channel is meaningful only in the context of a conferencing or mail application. This is indicated in Table 1 with the application classes shown in the second and third rows. We have not really considered voice as an upstream traffic type with data as downstream, since this basically implies voice command through speech recognition, which in essence is covered by data transmission on the upstream.

Many of the above applications can be classified under a general category: *Distribution services*, where content like software, books, music, video movies or programs etc, can be distributed electronically from central repositories to the computers of the users.

When no upstream connection is utilized, a large number of applications emerge, similar to the *subscription applications* that are available today through the analog channel TV. Subscription applications for a digital downstream channel transferring data, audio or video, are similar to program subscriptions in the case of analog downstream transmission. So, data subscription, as well as real-time audio and video subscription applications emerge (e.g., a real-time audio subscription application is subscription per radio station). Similarly, a large number of applications will be developed that relate to broadcasting data, audio or video.

3.2 Real-Time Applications

Real-time applications require that media are delivered to the user in an isochronous fashion. The high bandwidth of HFC networks enables such applications, which in addition to interactive applications will provide the end-user with the ability to do business and bring improved entertainment to the home.

Using a full-duplex data connection to the H/E, one can bring multimedia applications to the end-user who will be able to browse and request delivery of video, audio and data from digital libraries and repositories. Such applications will provide a new means of *remote training and education* in the home, school or workplace. *Entertainment* is also a vast area of applications in this class, since it becomes feasible to provide *multi-player digital games*, where several players may be simultaneously active on the same game board, or similar applications. Such services can also take advantage of the broadcast nature of the network, allowing multiple users to view the common information simultaneously.

When the downstream connection delivers digitized audio or video, it becomes feasible to deliver real-time Audio-on-Demand (AoD) or Video-on-Demand (VoD) services to the user (audio/video streaming). A customer will be able to have, for example, real-time music delivered and played on his/her station, on a demand basis. *Personalized radio or TV stations* will deliver to users the desired series of songs/programs (or simply the desired type of audio or video content). In the case of video, which will be compressed to alleviate the low bandwidth available for the digital downstream connections, several real-time schemes may emerge: Video-on-Demand (VoD), Near Video-on-Demand (NVoD), video previews, "personalized" video programs, etc. The ability to deliver digital audio/video to the end-user will be significant to the advertisement industry, since it will become feasible to provide audio and video previews to a large body of potential customers (in either real-time or non-real-time). The broadcasting nature of the medium will enable efficient and cost-effective delivery of such services.

Coexistence of the digital upstream connections with the analog downstream will enable applications that combine (synchronize) these connections. An immediate set of services is the body of applications where currently telephone orders are made for TV services, such as pay-per-view and time-based subscription —i.e., subscription to channels for certain time windows. The digital upstream can be effectively used to deliver to the H/E all information that is currently provided by telephone.

As mentioned previously, audio or video information in the digital upstream channel is meaningful only in the context of a conferencing or mail application. The real-time applications with audio and video upstream, that are envisioned for the near future, are the conferencing applications. Asymmetric conferencing accommodates the cases where only one of the 2 conferring parties has the support for video conferencing, while the second party has only the ability of audio conferencing; asymmetric conferencing applications allow for interoperability of audio and video conference systems. The broadcasting characteristic of the medium enables multi-party conferencing easily.

Over HFC networks, POTS-like telephony is also expected to be provided. Although we do not expect that HFC telephony will ever replace regular POTS as the main means for residential voice communications, the ability to add dynamically a second, or a third, etc, "telephone line" for services like faxing or data/teleconferencing over the same medium, is quite appealing. We expect that the HFC networks will provide a "virtual copper wire" conduit to POTS providers. This will save money for both the customer and the POTS providers, who will not have to lay and maintain extra telephone lines.

The last row of the applications in Table 1 corresponds to cases where no upstream information is necessary for the application implementation. The analog downstream, for example, corresponds to the conventional CaTV environment, where no upstream channel exists. So, applications such as broadcast TV and premium channel subscription fall in this category.

Similar to subscription in the case of analog downstream transmission, one can easily envision subscription applications in the case of a digital downstream channel transferring data, audio or video. Furthermore, as far as data are concerned, one can easily deliver applications such as TV program schedules and information, video-game download, and news distribution as part of data broadcasting applications.

4 Full Service Requirements

Current CaTV systems are basically isolated islands that consist of a H/E and the residential community that the particular H/E serves. The only information currently carried by traditional CaTV is TV programming in one-way broadcast mode. On occasion, low rate digital data can be transmitted during the vertical retrace interval. Since this feature results in too low data rates (< 16 Kbps) to be used for broadband and even for most narrow-band applications, it is given no further consideration in this paper.

Hence, most of the services discussed in the previous section cannot be provided automatically just because the CaTV operator has simply enabled two-way communications on its access network. As CaTV operators upgrade the access network side of their plants, they must do so on the "other side" as well. They need to provide the means through which the service providers can access the high-speed HFC access networks and make their services available to the CaTV customers, as shown in Figure 4.

In a CaTV tree-and-branch network, the H/E, which is located at the root of the tree, is the natural choice for connecting servers. So, we believe that in "first-generation" two-way HFC systems we will see service providers being directly connected to the H/E, either by being physically located at, or close to, the H/E, or being connected through permanent leased high-speed telephone connections. This service provision model has been adopted today by the majority of the two-way HFC trials [13]. Therefore, the H/E needs to be equipped with the necessary high-speed interconnection devices, e.g. high-speed FDDI LANs if the service

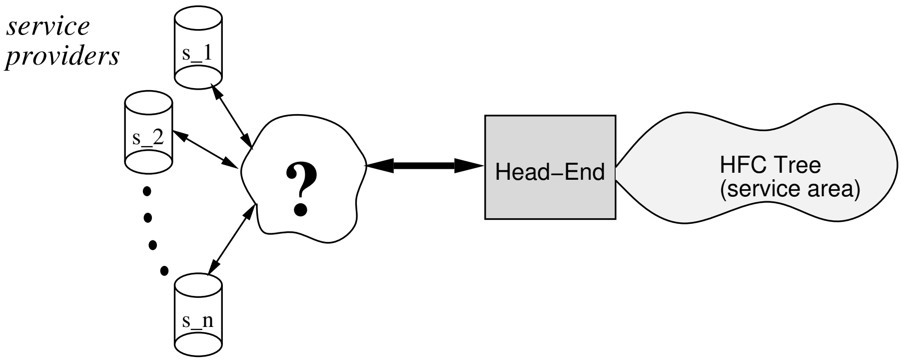

Figure 4: Preparing a CaTV system to provide data-over-cable services

providers are located at or near the H/E site, or ISDN, T1 and T3 telephone equipment for connection to remote service providers over leased lines, as shown in Figure 5.

Without a doubt the most popular service, at least at the outset, will be Internet access. This is the most requested service, and given the fact that many service providers can also carry their services over the Internet, an Internet connectivity of the highest quality will be an absolute necessity from day one of an HFC system operation. This implies that the CaTV operators must carefully choose a highly reliable *Internet Service Provider* (ISP), that provides not only excellent customer service 24 hours a day, 7 days a week, but is willing, if it has not done so already, to support high-speed connectivity between the H/E and the ISP location, and of course between the ISP and the Internet itself. This means that high-speed telephone connections must be activated between the ISP and the H/E. Alternatively, high-speed HFC, or microwave connections in case the H/E and the ISP are in a line of sight of each other, could be installed, bypassing entirely the telephone network. The CaTV operators may choose to be Internet Service Providers themselves.

When it comes to Internet access, the H/E can act as a *router* and an *intelligent hub* to direct traffic to and from the customer and the Internet. On the other hand, through simple statistical analysis of the customer traffic, the H/E can also serve as a *local cache*. It can efficiently and intelligently pre-fetch from the Internet a plethora of popular pieces of data, and make them available to the customers as soon as they are requested. The Web itself can assist in that. There exist a plethora of Web search-engines that can help locate and pre-fetch easily important pieces of information. As a matter of fact, there exist even top-100 Web page collections covering a wide range of topics.

As the number of service providers and their offerings increases, and the customers diversify their interests, providing direct connections to certain service providers, or caching

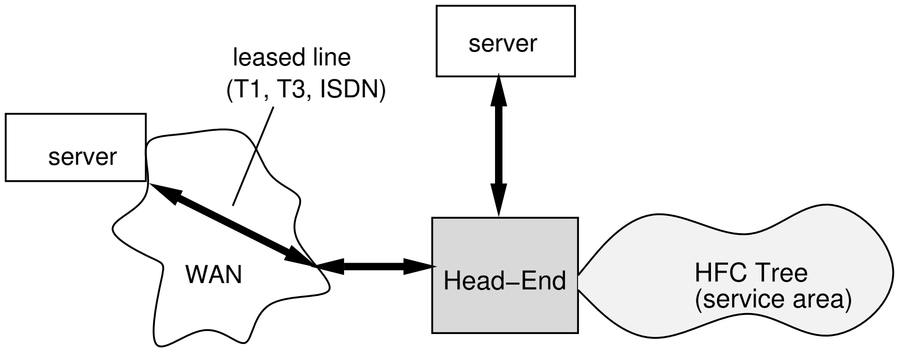

Figure 5: "First-generation" data over cable networks

information locally may become irrelevant. In this case, it will be better to leave it to the customer to select and access the particular services he/she desires. Most probably, these new services and service providers are not going to be located within or near each community served by a CaTV system, but rather would be located anywhere on the globe. So, the network architecture will have to be enhanced and gradually migrate from locally- and directly-attached service providers, to service providers connected at the customers' will to the H/E over switched high-speed broadband networks as shown in Figure 6. This will require the H/E to further upgrade its interconnection equipment and be able to support switched broadband traffic over, for example, ATM, which is the network of choice for broadband communications. We need to remark here that the IEEE 802.14 MAC will carry ATM cells as one of its payload types. Moreover, the residential broadband (RBB) group of the ATM Forum is working on defining ATM services over 802.14-compliant HFC networks.

It should be emphasized that an HFC network provides only an efficient interconnection means for delivering a wide range of broadband applications to end-users. Yet, services may not be effectively provided even with the end-to-end high-speed connectivity. All the information and intelligence necessary to build an application is located at a service provider site. Thus, the service providers too may have to upgrade their infrastructure to be able to provide interactive broadband services to individual customers.

Contrary to broadcast services, which will continue to be prominent among the CaTV users, who take advantage of the simplicity of the one-size-fits-all approach, the interactive data services discussed in the previous section require that service providers address the needs of their customers. Interactive data services require highly intelligent computer and communication systems that will be able to adjust on-the-fly to the requests received from

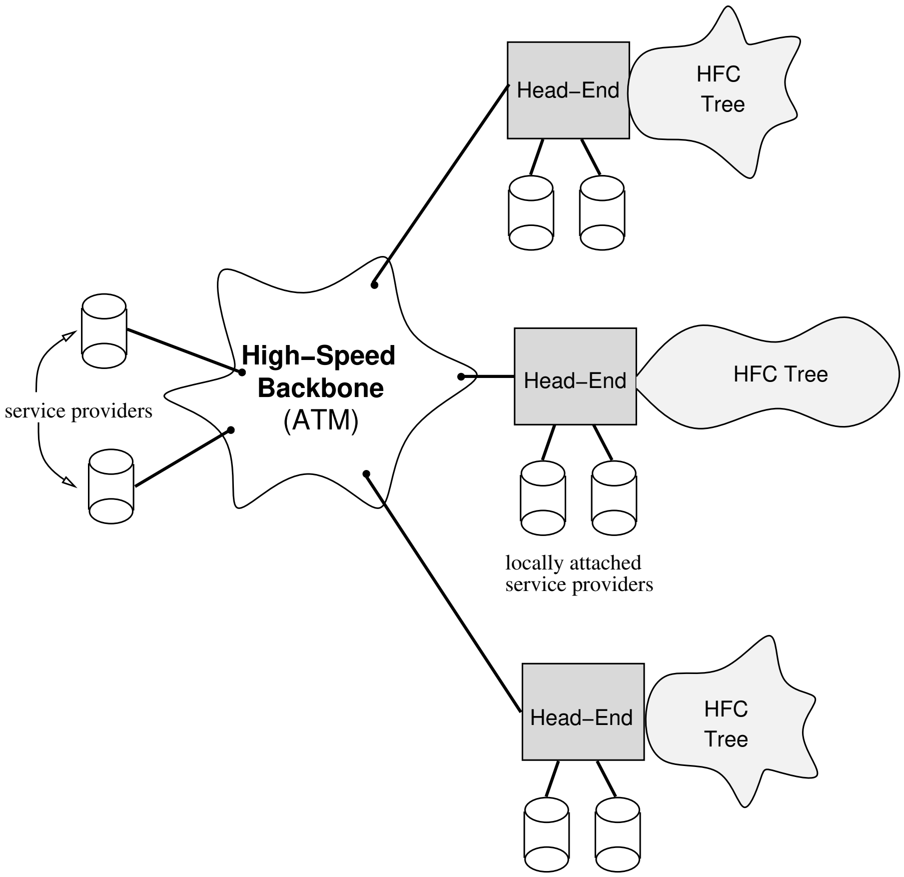

Figure 6: Full-connectivity end-to-end high-bandwidth solution

a diverse collection of individuals. Therefore, we foresee that the development of "personalized" interactive services will also spur plenty of activity in the areas of: (a) specialized server architectures for supporting large storage and powerful high-speed I/O subsystems; (b) high-speed interconnection networks between the server components and servers, in general; and (c) sophisticated management and control systems.

In the end, it all boils down to the fact that to provide a service to a customer that requires high bandwidth and low response times, the high bandwidth has to be available throughout the path from the server site to the customer, and also both the server and the customer must have the appropriate equipment that can support the requested service.

5 Concluding Remarks

In this paper, we have discussed issues pertaining to bringing digital services to residential customers. We have identified two major players in this area: the telephone and CaTV service providers. This paper has been focused on the CaTV solution.

As cable operators upgrade their all-coaxial networks to HFC networks, they also modify them to enable two-way data transport on them. Cable systems with an abundance of excess bandwidth are hence getting ready to transport digital data at tens of Mbps speeds. At such high speeds a new breed of data services could be possible, that will supplement enhanced versions of already existing ones. In this paper, we have highlighted several such applications. To provide these applications, one needs to establish an end-to-end, i.e. from the data server location to the customer, high-speed data transfer infrastructure. We have presented possible solutions and migration paths on how this can be achieved.

We have also discussed the possibility of high-speed data communications over telephone lines. The big plus for this approach is that the analog telephone service and the copper telephone wires are practically ubiquitous. On the other hand, the big plus for the CaTV approach is that it can provide unprecedented data speeds to customers. We believe that the latter will be the defining factor in choosing CaTV over telephone data services, whenever the option is available.

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