AN ENGINEERING COST AND POLICY ANALYSIS OF INTRODUCING FIBER INTO THE RESIDENTIAL SUBSCRIBER LOOP

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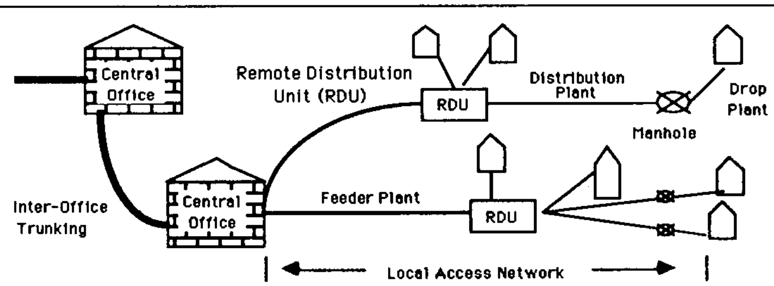
1. Introduction

Recent advances in optical transmission technology have spawned numerous proposals to deploy broadband fiber optic networks that would reach every household and provide the infrastructure for a wide array of new communications services. Before such a vision can be realized, however, numerous technical, economic, marketing and political barriers must be overcome. This study presents an analysis of the principal engineering and economic issues that have emerged as telephone companies consider rewiring the nation's residences with fiber optics.

Engineering cost models have been developed to estimate the capital costs of replacing the existing copper wire subscriber loop plant with fiber optic connections. The models determine the installed first cost of a network from the central office of the local exchange carrier (LEC) out to the subscriber's premises. As suggested by Figure 1-1, these costs include equipment at the local central office, feeder cable, remote electronics (if any), distribution and drop cable, and network termination equipment on customer premises. We assume medium term (5 to 10 years) technology options in order to examine the economic implications of alternative optical network architectures. In addition, the analysis considers several regulatory questions which are raised by the results of the models.

Figure 1-1. Telephone System Local Subscriber Loop Plant



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Residential Broadband Networks

Replacement of the existing copper plant with fiber could provide the capacity for new broadband services such as entertainment video, high-definition television (HDTV), high-speed data transmission, or image databases. By comparison, copper plant, while adequate to provide existing services like voice, packet data, or conference-quality video, can only carry signals of a few megabits per second, and then only if repeaters are installed every few thousand feet. Yet the design and implementation of a ubiquitous fiber optic network is a daunting task. The different transmission characteristics of fiber require revisiting and revising many of the engineering precepts fundamental to copper network design.

- Should switching functions be concentrated in large central offices connected to long fiber optic loops to each customer, or distributed throughout the network to allow for more sharing of the fiber plant?

- What multiplexing schemes should be employed to increase the capacity of the fiber? What is the cost-effective capacity of a fiber?

- What role does fiber play in the technical evolution of the network? What are the generic attributes of a network architecture which allow an efficient migration to future technologies?

In addition to engineering issues, a number of economic and marketing questions must be addressed.

- What new service revenues would be required to justify residential fiber networks? What services might generate these revenues?

- How is the financial feasibility of a broadband network affected by assumptions about the time it takes to build up a sufficient subscriber base? Can capital spending be scaled to different rates of subscriber demand, or must the bulk of the investment be made up front?

- How do capital costs vary with network architecture?

A fiber optic subscriber network raises numerous policy questions as well.

- Are there sufficient economies of scope in the joint provision of voice and video services that existing policies mandating their separation should be reconsidered?

Within the confines of this paper, we cannot possibly address all these issues. However, we hope our analysis sheds some light upon many aspects of these issues and will contribute constructively to the ongoing policy debate. Our focus is on fiber networks to the home; broadband networks and services for businesses are not addressed.

2. Key Concepts in the Design of Residential Fiber Optic Networks

Four concepts are fundamental to an understanding of fiber optic loop design alternatives: first, the characteristics of fiber technology; second, the principal alternative topologies for subscriber loop architecture; third, the relationship between architecture and services; and fourth, ongoing changes in the network.

Fiber Technology

The use of light to carry signals over long distances is not new. In the atmosphere, transmission is limited to line of sight and can be disrupted by fog and rain. A thin glass fiber can carry a lightwave hundreds of kilometers through buried conduits. The information carrying capacity of the fiber is limited primarily by the electronics and the electro-optics (sources and detectors). Typically, a laser or light emitting diode (LED) light source is turned on and off rapidly to carry digital information; rates as high as several gigabits per second have been achieved commercially. The International Consultative Committee for Telephone and Telegraph (CCITT) has defined a family of standard digital rates for communicating over fiber. The synchronous optical network (SONET) standard describes a family of synchronous transport signals (STS), each designated STS-M to represent an electrical signal supporting signals of M x 51.84 Mbps (the STS-1 rate) (Boehm, Ching, et al. 1986; Boehm 1990). Alternatively, an analog signal can be used to modulate a more expensive laser. Analog modulation (AM) is attractive for the carriage of analog television signals.

Power Budget. An important characteristic of a fiber network system is the optical power budget. Optical signal power produced by the transmitter is attenuated by distance, connectors, splitters, optical couplers and splices. The optical power budget represents the maximum amount of attenuation which is acceptable for a given transmitter receiver pair, at a particular data rate. (Because receiver sensitivity declines at higher data rates, the power budget is data rate specific.) Digital systems will typically have a higher power budget than AM systems, and can thus use less sophisticated transmitters and receivers.

Wavelength Division Multiplexing. More than one light source, at different colors or wavelengths, can be transmitted on a fiber simultaneously; this is referred to as Wavelength Division Multiplexing (WDM). Passive optical elements are used to merge or select a specific wavelength (Hill 1990). An optical source produces not a single wavelength but a range of frequencies (referred to as the linewidth). For broad linewidth sources, very few channels can be combined using WDM because the spectra of the sources will overlap and interfere with each other. Light emitting diodes (LEDs) have a very broad linewidth, on the order of 5000 to 10,000 GHz, while lasers have narrower linewidths, varying between distributed feedback (DFB) lasers at 100 MHz to Fabry-Perot lasers at 300 to 600 GHz. Given the three low attenuation windows of transmission over fiber, Hill estimates that 14 to 21 channels per fiber window would be a reasonable number of channels to expect using laser sources and WDM (Hill 1990). A common use of WDM is to provide upstream and downstream communication on a single fiber using two different wavelengths.

Network Topology

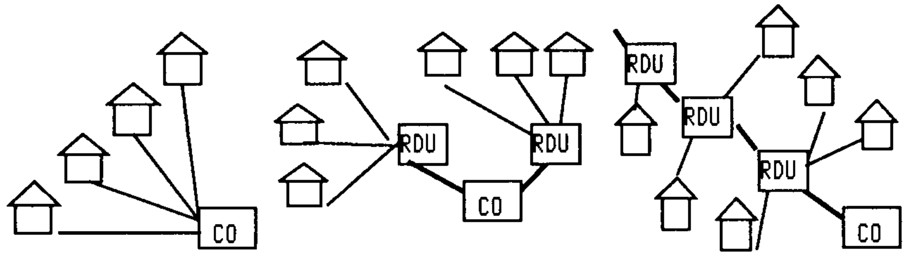
Three topologies fundamental to most network architectures are the star, double star and bus. As shown in Figure 2-1(a), the star topology runs a single cable from the central office to each subscriber. This topology has the advantages of high capacity connections (the bandwidth of the cable is not shared with any other subscribers), privacy, and simple network equipment, all at the expense of having to deploy more cable in the network.

The double star network in Figure 2-1(b) introduces a remote distribution unit (RDU) which uses either multiplexing or switching techniques, or both, to reduce the amount of feeder cable by sharing this plant over more subscribers. Below the RDU, the network is identical to the star. While the double star offers the same advantages as the star, the drawbacks are that RDUs can be expensive to install, require power to operate, and increase network maintenance duties. The double star network is efficient if sufficient transmission economies (also known as "pair gain") can be gained from combining the signals onto a feeder cable. The second leg of the double star then can efficiently distribute the switched signals. The attractive feature of this topology is that it can provide a mix of distributive and switched services because the shared feeder cable can efficiently carry the distributive information to the RDU.

The bus topology in Figure 2-1(c) has the advantage of deploying common plant throughout the network. The disadvantages are the high number of remote nodes (each requiring power), the decrease in bandwidth available to each subscriber, and potential loss of privacy. This topology is best suited for distributive services because each subscriber receives the same transmission signal. It can be applied for switched services if the bus cable provides enough channels to assign one or more channels uniquely to each subscriber.

Viewed together, the star architecture represents the extreme case of deploying virtually no common plant in the subscriber loop; it is preferred when the cost of transmission is low relative to the cost of switching. The double star represents a middle ground by deploying common plant in the feeder loop; while the bus represents the opposite extreme by sharing plant throughout the entire network. It is preferred when costs of transmission are high relative to switching.[1]

Figure 2-1. Alternative Local Access Network Topologies



(a) Star (b) Double Star (c) Bus

Broadband Services

The optimal network architecture will vary with the services to be provided. In the past, the LECs have used a switched star network with a dedicated channel to each subscriber, to provide network access using inexpensive copper wire pairs. Conversely, cable television provides an identical set of entertainment video channels to every subscriber. To distribute these *non-switched* video services, the cable companies install coaxial cables in tree and branch networks with very little dedicated network plant per subscriber. With the uncertainty surrounding which broadband services a LEC might find profitable, or even be allowed to carry, it is not surprising that a wide array of architectures have been proposed to connect fiber to the home. Moreover, the fiber-based architectures designed only for narrowband services differ markedly from those carrying an integrated mix of narrowband and broadband services.

With regard to the LECs, we believe the justification for installing fiber to the home lies primarily in the possibility of providing new *broadband* services to the subscriber. Such services can be categorized as either *communicative* (interactive communication) or *broadcast* (mass distribution). To date, entertainment video has been the only broadband service to demonstrate the ability to derive substantial revenues from the residential market. This includes distributive video, similar to present cable and pay television services, and some form of an on-demand video library service, which is a one-way communicative service. We focus our attention on those fiber-based architectures that can provide these essential broadband services. Video telephony, a two-way communicative service, is not considered likely to be significant in the time frame of our study.

A key issue for residential networks is the data rate of a video signal, the value of which represents a trade-off between the available transmission capacity versus the cost of compression and desired signal quality. The STS-3 rate (155.52 Mbps) is more than adequate to carry one, uncompressed, NTSC-quality video channel. Further, experts anticipate higher-quality video signals, such as Extended Quality Television (EQTV) or HDTV, can be easily compressed down to the STS-3 rate (Rzeszewski 1988) and, at higher cost, even to the STS-1 rate. Conservatively, we assume that each NTSC video signal is either digitized for transport within a STS-3 payload or can be compressed to fit within the STS-1 payload.

Network Evolution

A fully fiber network providing a complete range of broadband services will not appear overnight. Rather, both the services provided, and the extent of fiber in the loop will evolve over time.

A Dynamic Investment Problem. A local exchange carrier planning to use fiber in the subscriber loop need not provide all possible services from the beginning. Fiber and associated electronics may be introduced to carry only narrowband services at first, and later be upgraded to carry video. The dynamic nature of network evolution further complicates the process of selecting an optimal network architecture. A local exchange carrier planning to convert its local loop plant to fiber optics over the next twenty years must determine the optimal timing for a sequence of investments (Reed and Sirbu 1989). In the future, fiber technology will cost less; but waiting means deferring potential revenues from broadband services. Moreover, delay may permit a competitor to preempt future revenues by installing a fiber system. However, given the present immature state of the technology, an initial architecture, designed to carry only narrowband services, may differ from the one that would be chosen if investment were deferred or more services were to be offered from the beginning. Several current trials of narrowband services over fiber use a bus approach because it minimizes the amount of expensive fiber. However, the cost of upgrading a bus architecture to carry switched video services may be higher than for other designs.

Optical Digital Loop Carrier. Fiber need not be introduced all the way from the central office to the subscriber's premises. Already carriers find it attractive to use fiber from the central office to a RDU closer to the subscriber. A few fibers are used to multiplex the narrowband traffic for up to a few thousand subscribers, saving the cost of running as many copper pairs to the RDU. The cost of the multiplexing equipment and the RDU is shared by these subscribers. This approach is referred to as optical Digital Loop Carrier (DLC) because the signals are digitized to facilitate the multiplexing in the feeder loop. Also, putting fiber into the network down to the RDU places a potential broadband link closer to the subscriber. Yet despite its appeal, the cost of DLC has restrained deployment of the technology to areas located a long distance from the central office, though deployment is growing. In 1988, Bellcore reported the prove-in distance for a DLC system was 5.5 kilometers (18 kft) (Taylor and Kimsey, 1988). In 1989, 7% of subscriber pairs were served by a DLC system, of which 5% were copper-based systems and 2% were fiber-based systems (Vanston, Lenz, et al. 1989).

Fiber-to-the-Curb. The high cost of installing all-fiber networks in the subscriber loop has forced telephone companies to search for more cost-effective, short-term strategies for deploying fiber. Consequently, the industry now proposes *fiber-to-the-curb* (FTTC) or *hybrid* fiber/copper networks which lower investment costs by reducing the amount of fiber in the network and by using portions of the existing copper network. The term hybrid reflects the use of both fiber and copper cable in the same system.[2]

Extending fiber past the RDU to a pedestal or manhole at the curb (Figure 1-1) offers several advantages by:

- exploiting the high capacity of fiber through sharing the transmission facilities over more subscribers in the distribution portion of the network;

- placing a potential broadband link closer to the subscriber while postponing investment in fiber drop plant — a significant saving because the cost of the drop plant cannot be shared over many subscribers.

Hybrid systems are attractive if they can provide narrowband services at low cost, but they raise a number of difficult issues. Does the approach actually reduce network costs relative to those incurred by using existing copper technology to provide the same level of narrowband services? How will the presence of electronics placed in every pedestal affect operations and maintenance of the network? From what source and in what manner will the pedestals receive electrical power? And most important, how cost effectively can the system be upgraded to offer broadband services? Despite these questions, less than two years after the first hybrid system was announced, a proliferation of proposals and field trials are well under way.[3]

3. Optical Network Architectures for the Subscriber Loop

This study considers alternatives available to telephone companies for introducing fiber in the network classified by topology, the extent of fiber used and the services carried by the network. Table 3-1 lists the network alternatives chosen for this analysis. The alternatives include hybrid fiber/copper as well as all fiber systems, and the services range from narrowband-only to distributed and switched video (video on demand) services. In this section we describe the alternatives in sufficient detail to enable the construction of the engineering cost models described in Section 4.

Optical Digital Loop Carrier

Figure 3-1 illustrates a schematic diagram of the DLC network architecture. Central office equipment includes a multiplexer to combine and frame the DS1 signals (1.544 Mbps) from the switch, and the optical transmitter and detector unit (shown as a laser transmitter and PIN photodetector[4]) connecting to the feeder fiber. In the feeder network, the fiber carries multiplexed voice circuits at multiples of the STS-1 rate

Table 3-1.
Network Alternatives by Extent of Fiber and Level of Network Service

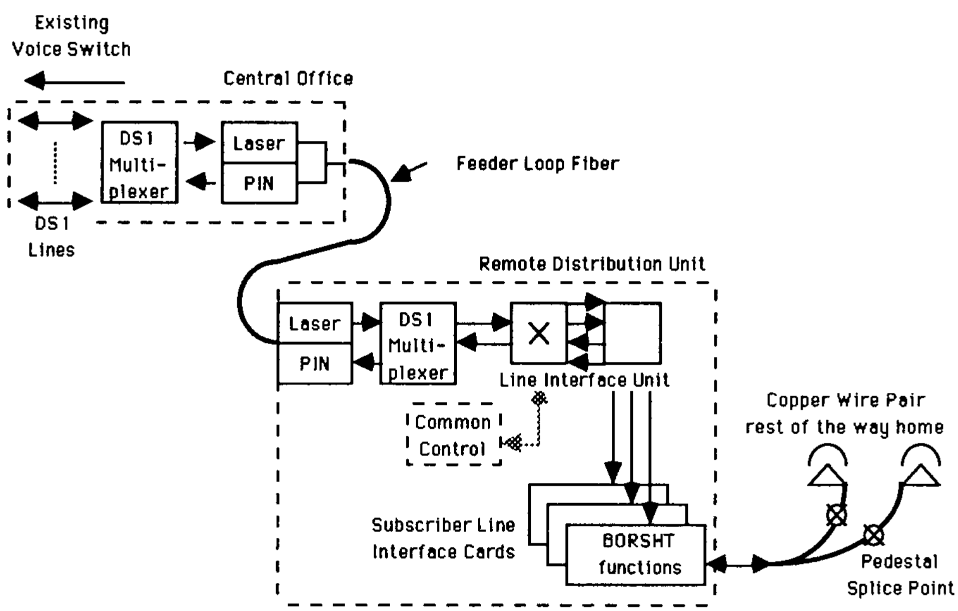
Network Alternatives	*Narrowband Services*	*Distributed Video-Service*	*Switched Video Service*
Optical Digital Loop Carrier	❑		
Fiber/Copper Hybrid (Fiber-to-the-Curb)	❑		
All-Fiber Narrowband Network (POTS on Fiber)	❑		
Fiber/Coaxial Cable Hybrid (Overlay Fiber-to-the-Curb)		❑	
Fiber/Coaxial Cable Hybrid (Fiber-to-the-Curb)	❑	❑	
All-Fiber, Distributed Video Network	❑	❑	
Integrated Broadband Network, Switched Video	❑	❑	❑

between the central office and the RDU in a logical star design. The multiplexing equipment handles up to STS-2 signals. The demultiplexer reduces the STS-2 signal at the RDU into DS1 signals that feed into first and second stage subscriber line interface channel banks, which distribute the voice signals to the appropriate copper wire pair at the DS0 rate (64 kbps). The first unit acts as a first stage switch and directs the signals to the correct second stage unit, which directs the calls to one of 96 copper lines. The subscriber line interface cards provide the BORSCHT functions (battery, overvoltage protection, ringing, signaling, codec, hybrid, and testing). The design of the remaining network below the RDU follows the normal planning rules for copper networks. Copper pairs run from the RDU to a terminal housing, one for every eight households, and then to a residence equipped with a standard N-ISDN telephone.

The equipment shown in Figure 3-1 excludes the telephone switch in the central office. As a rule, the costs for central office switching components are included in the calculations only if they represent a necessary addition to the existing central office (e.g., a broadband fiber network requiring a video switch at the central office).

Unlike metallic media, optical fiber cannot carry enough electrical power to operate the network components. As a result, decentralized electronics equipment must be powered, either by a direct connection to a local commercial power outlet, or by a separate copper network. This is a problem for all subscriber loop networks using fiber because there must be a point in the network where the conversion from optical to electrical transmission occurs. This location is known as the optical network interface (ONI), and whether the ONI is located at the RDU, the curb, or the home, it will require equipment to provide continuous and backup power.

Figure 3-1. Digital Loop Carrier Architechture



Consequently, the ONI and its power source is an important element of any network architecture. In the case of a DLC system, the ONI is located at the RDU. The engineering planning model assumes the standard industry practice for powering DLC systems. A connection from the local public utility provides electricity for the RDU electronics and the RDU houses enough batteries for eight hour emergency backup in case of loss of commercial power (Luniewicz, Olson, et al. 1984). Protection of the high-speed electronics housed in the RDU requires a controlled environment vault (CEV) to provide air conditioning, power, and power backup.

Narrowband Fiber/Copper Hybrid

While a number of hybrids have been proposed to deliver narrowband services, this study restricts attention to two approaches: a bus architecture similar to a system proposed by Raynet Corp. (Dawson 1988); and a variant of the Passive Optical Network architecture described by Faulkner, Payne, et al. (1989).

Passive Double Star Architecture. In a Passive Optical Network, signals for multiple subscribers are multiplexed on a single fiber emanating from the central office. Using optical splitters, the signal fans out to multiple fibers at one or more points closer to the subscriber. (Figure 3-2) In this way, PON networks reduce costs by sharing transmission resources. Larger bandwidth signals have smaller power budgets, so broadband services cannot be split as often as narrowband signals. An advantage of PON networks is that they provide a transparent path between the central office and the subscriber. This provides a degree of flexibility since the architecture is dependent upon the power budget and not the transmission format. The use of passive devices reduces the number of potential points of electronic equipment failure.

In the PON passive double star configuration (upper portion of Figure 3-2), a single feeder fiber carries the multiplexed voice channels intended for eight pedestals, at most equivalent in capacity to four DS1 lines. At the RDU, a passive power splitter divides the feeder signal into eight identical copies, one for each distribution fiber attached to the splitter. Upstream signals travel over the same fiber using coarse WDM where the power splitter now acts as a coupler to combine the signals from each pedestal. A ranging protocol provides the correct timing of transmission for each pedestal to avoid collision of the signals.

The pedestal houses the ONI, which is shared over eight households. Each subscriber requires a card to process the N-ISDN signal (two voice channels along with a 16 kbps data/signalling channel) and convert it to analog format for transmission over copper wire pairs to the subscriber. The drop and CPE is the same as in the DLC model.

Bus Architecture. The hybrid fiber/copper bus architecture assumes a bus topology in the distribution network. As shown in the lower portion of Figure 3-2, each fiber from the central office connects eight pedestals, each serving eight subscribers, together on an optical fiber bus. Every feeder fiber carries the narrowband traffic of 64 subscribers, again equivalent in capacity to about four DS1 lines. This low bit rate reduces the complexity and cost of the electronic components, and decreases the level of environmental protection required by the pedestal electronics.

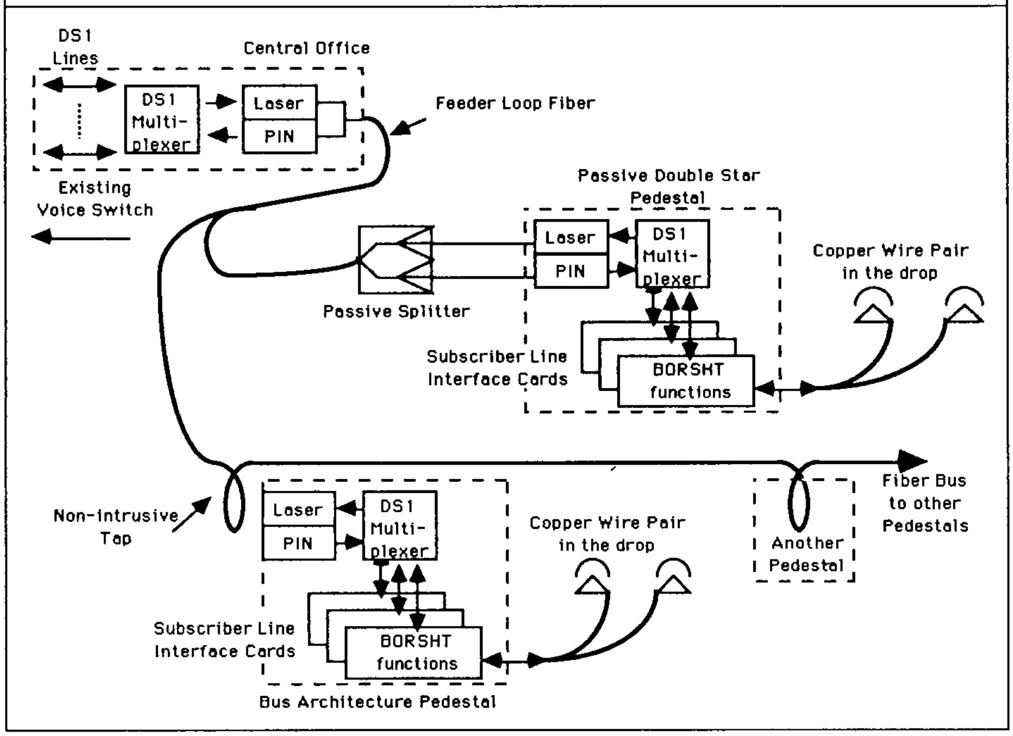
At each pedestal, a receiver detects the downstream signal using a *non-intrusive tap.* This type of tap places a bend or crimp in the fiber cable so that portions of the downstream optical signal will escape out of the fiber for detection by a normal receiver.[5] In the same manner, the pedestal transmitter inserts the upstream signal onto a separate fiber dedicated for upstream transmission through a non-intrusive tap. A ranging protocol determines the correct timing to insure that the information does not collide or interfere with other time slots on the bus. The subscriber line card, drop, and CPE are the same as the passive double star hybrid network.

The fiber/copper hybrid models assume power is supplied to the pedestal by a nearby commercial power outlet and the pedestal houses eight hours of emergency backup power for voice service.

All-Fiber Narrowband Network

The analysis considers two architectures, the active and passive double star approaches, that rely exclusively upon optical fiber transmission links to deliver narrowband services to the subscriber.[6] In both cases, because the ONI is located on the subscriber premises, provisions must be made to power the CPE. The actual location of the ONI is a function of the degree of environmental protection required of the equipment versus the access required to maintain its operation. Many field trials have placed the ONI in

Figure 3-2. Fiber/Copper Hybrid Architectures



the safer environs found inside the garage, but on a large scale this arrangement may be unacceptable for service reasons (Bickers, Rowbotham, et al. 1990; Bourne 1990, No,. 54). Both of these models, and all subsequent models placing the ONI at the home, assume power for the ONI comes from a local connection to the subscriber's commercial power outlet. To ease the task of maintaining batteries and to capture any economies of scale, the pedestal provides back-up battery power for the ONI electronics for eight subscribers.

Active Double Star. The active double star architecture resembles the digital loop carrier system of Figure 3-1 but with fiber transmission links in the distribution and drop portions of the network. These fiber links are identical to those assumed for the IBN active double star alternative described below.

Passive Double Star. For this case the fiber portion of the passive double star architecture described in the last section extends to the subscriber instead of the pedestal. The pedestal holds a passive splitter that further divides the signal carried over the distribution fiber into eight parts, one for each subscriber served by the pedestal.[7] With the ONI located on the subscriber premises, the RDU and pedestal locations of the network hold passive devices and do not require electrical power.

The data rates of the system are unchanged from the hybrid network. Because the signals of several subscribers come into each household, the problem of securing the information privacy of each subscriber becomes an issue.

Fiber/Coaxial Cable Hybrid

The telephone company might consider a fiber/coaxial cable hybrid network to deliver distributed video services either together with telephone services or on a separate network alongside their existing narrowband network. In both cases, the hybrid network consists of fiber upstream from the pedestal and coaxial cable in the drop to carry distributed video services.

Distributed Video Overlay Network. The overlay network would run parallel to the narrowband network. The two would share the same trenching, cable, and pedestal housing. However, the narrowband and distributed video services are not integrated in the sense that a different fiber is used to transmit each service. The reason a telephone company might chose to operate two networks side by side is that the power budget available for narrowband transmission is substantially larger than that for video transmission. Thus, the bandwidth of the hybrid fiber/copper system cannot easily be increased to carry distributed video services by putting in new electronic components (see Jensen and Weeks 1990; Menendez and Vogel 1990; Weeks and Jensen 1990). For example, the design of the bus architecture using non-intrusive taps conservatively assumes eight nodes on the fiber bus, resulting in at best a splitting loss of 9 dB. Given the minimum received power for a 30 channel AM video transmission system is about 12 dB, at most 3 dB remain in the power budget (an insufficient amount) to cover the remaining splicing, connector, and transmission loss.[8]

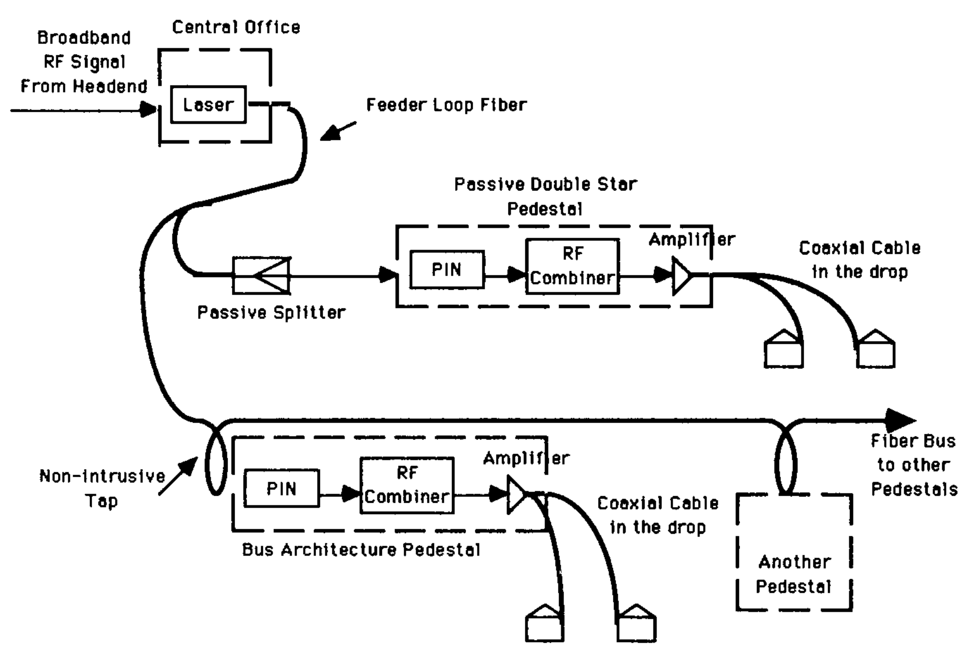
Figure 3-3 shows two overlay network architectures using the passive double star and bus architectures. Both architectures are companion networks to the narrowband hybrid fiber/copper networks introduced above.

The hybrid fiber/coaxial cable network with a bus architecture differs from its narrowband counterpart. The smaller power budget for broadband leads us to reduce the number of nodes on the fiber bus by one half and increase the number of households served by the broadband electronics in a pedestal from 8 to 16. Raising the number of households served per pedestal increases the distance of the coaxial cable drop, which is limited to a distance of about 250 to 500 feet before there is a need for an amplifier. The smaller power budget of an AM system dictates the use of two fibers to provide 64 channels of distributed video service. Thus, the broadband fiber bus is actually two fibers, each carrying 32 channels, running side by side between the central office and the pedestal.

The limited power budget available to the AM video system reduces the number of video channels per fiber for the passive double star architecture as well. Whereas the narrowband scenario places an eight-way power splitter at the RDU, the broadband hybrid system places a four-way power splitter at the RDU. Each pedestal receives 64 video channels by connecting to two fibers carrying 32 channels apiece.

Figure 3-3 illustrates the similarity between the broadband electronics of these two architectures. The central office receives the broadband radio frequency signal from the headend consisting of the 64 amplitude modulated, vestigial sideband (AM-VSB)

Figure 3-3. Fiber/Coaxial Hybrid Distributed Video Network Architecture



channels. Each laser directly modulates 32 channels onto the feeder fiber. At the ONI the receiver detects the incoming optical signal and converts it directly to AM format ready to transmit over coaxial cable in a form compatible with existing television sets.

Integrated Narrowband and Distributed Video Hybrid Network. This integrated approach differs from the previous architectures in that the narrowband and distributed video services are carried over the same fiber. A hybrid, passive double star network requires fiber transmission links upstream of the pedestal, with copper pairs and coaxial cable running between the pedestal and the home. Over the fiber, coarse WDM techniques combine the narrowband services onto one of the fibers providing broadband services. The narrowband services transmit over one wavelength (e.g., 1500 nm.) in digital format while broadband services operate on another (e.g., 1300 nm.) using AM format. The electronic components are identical to Figures 3-2 and 3-3, except that a wavelength division multiplexer component is inserted in front of the pedestal equipment to separate the two wavelengths from each other.[9]

Integrated Narrowband and Distributed Video Fiber Network

The analysis includes an integrated narrowband and distributed video network case which assumes an all-fiber, active double star architecture, identical to its IBN counterpart described below, except that only 64 video channels arrive from the headend to be switched through the system (see Figure 3-6).

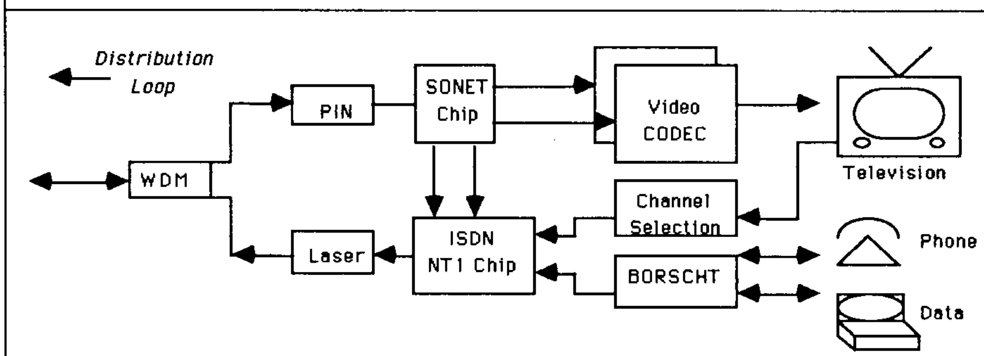
Integrated Broadband Network

The final alternative available to the telephone company is the integrated broadband network. The analysis considers a range of IBN network architectures including the switched star, active double star, and passive double star options. All IBN options assume digital switching and transmission.

An IBN requires the ONI to be at the subscriber's premises. Figure 3-4 shows a block diagram of the CPE employed in the star and active double star systems (the passive double star would also require a ranging protocol chip for timing upstream communications as well as a video decompression chip). After receiving the optical signal, the SONET chip demultiplexes the video channels and N-ISDN signal from the STS-12 signal into distinct video and voice channels. In addition, the chip provides the necessary framing and signal scrambling needed for digital transmission. The video codec converts the digital video signals to analog modulation for a standard television. All the models assume call set-up for voice and video is conveyed via the N-ISDN D-channel to the central office. Coarse WDM allows the use of the same fiber for the downstream TDM channels and the return N-ISDN channel.

Switched Star. The switched star architecture deploys a single fiber to every household in the network as illustrated in Figure 3-5. As is the case for all telephone company alternatives with broadband services, video and voice signals arrive at the central office on different incoming trunk lines where separate switching matrices handle each signal. All the switching functions occur at the central office, where a broadband digital crosspoint switch directs up to four STS-3 video channels to each subscriber. Coarse WDM allows the use of the same fiber for the downstream TDM channels and the return N-ISDN channel.

Figure 3-4. An Example of Customer Premises Equipment



Active Double Star. The active double star network reduces the amount of fiber required in the network by multiplexing several subscriber channels onto high-speed feeder fibers. Moreover, when multiple subscribers simultaneously watch the same television broadcast signal, a logical star must carry the same signal over the feeder cable many times. The active double star architecture deploys a remote switch that can take one copy of the network broadcast from the feeder cable and replicate it onto the distribution fiber of many households.

Figure 3-6 shows the block diagram for the active double star architecture. A SONET multiplexer combines the output of the video switching matrix to form a STS-48 (2.4 Gbps) signal for transmission over feeder fibers to the RDU. As many feeder fibers as are necessary to handle the estimated peak demand are devoted to downstream video traffic. Two separate fibers carry the multiplexed N-ISDN traffic, one for each direction. At the RDU, an avalanche photodiode (APD) detects the STS-48 signal, which is then demultiplexed into STS-3 rate video channels that input to a remote switching unit. The remote switch directs the on-demand video selections to the appropriate subscriber and replicates the distributed video channels to all subscribers. Simple demultiplexing of the N-ISDN signals alleviates the need for remote switching. Each subscriber receives up to four video outputs multiplexed together with an N-ISDN signal.

Passive Double Star. In a passive double star, multiplexers combine the signals for several households — by TDM, WDM, or both — onto a single fiber at the central office and distribute this signal throughout the serving area using optical splitting devices. This study addresses two alternatives:

- the digital signals intended for several subscribers are time division multiplexed together on a single fiber (Figure 3-7);

- the network has a set of wavelengths which it assigns to the subscribers, and the set of signals are wavelength division multiplexed together on a single fiber (Figure 3-8).

In both cases, all switching functions occur at the central office.

Figure 3-5. Switched Star Architecture

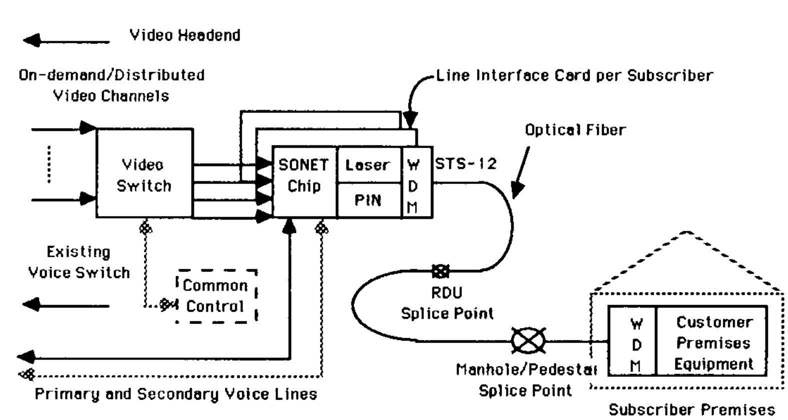
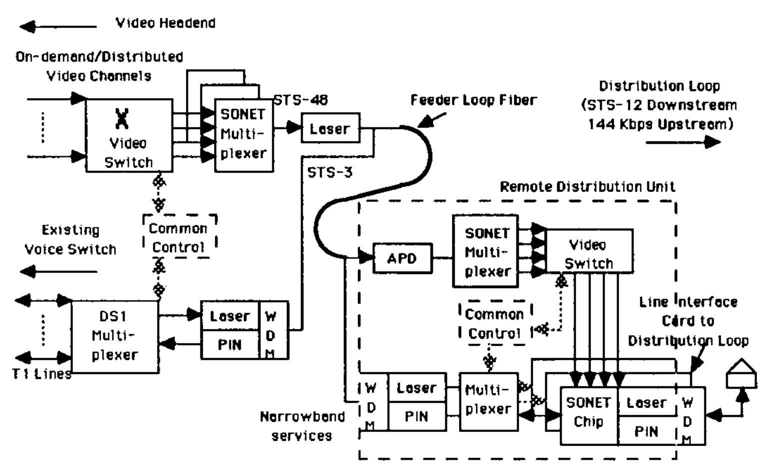


Figure 3-6. Active Double Star Architecture



In the TDM system, the RDU is a passive splitter which replicates the optical signal onto individual distribution fibers. Equipment at the subscriber's premises, using directions sent from the central office, selects the correct signal from the several multiplexed onto the fiber. A ranging protocol inserts the narrowband signals directed back to the central office into predetermined time slots using TDM. Of course, sending the signals of several subscribers into each household again raises the issue of privacy.

Originally, it was thought that cost and power consumption considerations of the microelectronics would limit the line rate feeding the demultiplexers on the subscriber's premise to below the STS-12 rate. However, some research groups believe that a gigabit per second line rate can be achieved by designing electronic equipment with a minimum number of high speed components. Cook, Faulkner, et al. (1990) reports a CPE unit which could handle a line rate of 2.4 Gbps using custom integrated circuits that these authors believe could be cost competitive in volume production with coaxial cable television equipment. Moderately more costly codecs allow reduction of the video channel rate to the STS-1 level to offer more channels per fiber. An STS-24 (1.2 Gbps) line rate would allow eight subscribers to be served by three channels each. This architecture economizes substantially on fiber by comparison with a single star, while simplifying and reducing the cost of equipment in the RDU (Hightower 1986).

Owing to the capacity limitations imposed by the cost of high-speed electronics in the TDM system, much of the interest in passive architectures has shifted to using wavelength division multiplexers instead of power splitters in the local loop (Lin and Spears 1989). The architecture is still a logical star topology, only now the multiplexing is done in the optical domain; the network assigns one wavelength per subscriber on the feeder fiber and the RDU only allows this wavelength to pass on through to the subscriber. This has the advantage of eliminating active RDUs from the network while still preserving the capacity per subscriber afforded by such systems.

Figure 3-7. Passive Double Star Architecture

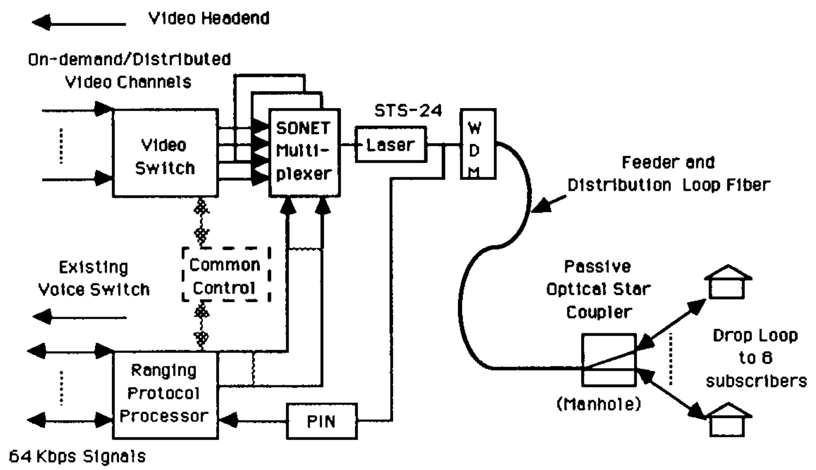


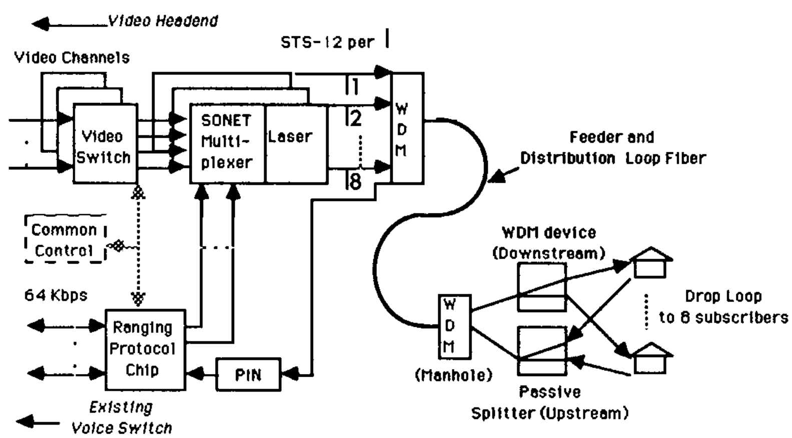
Figure 3-8 illustrates the WDM architecture where each subscriber is assigned a unique wavelength for communications. At the central office an optical source tuned to the correct wavelength transmits up to four STS-3 broadband channels downstream to the subscriber. The RDU is now an optical filter, blocking out all but one of the wavelengths headed downstream to the subscriber. The network termination equipment is independent of the particular wavelength used for communication. That is, the bandwidth of the optical receiver is wide enough to receive adequately all potential wavelengths. Alternatively, the CPE could include an optical filter which only passes certain wavelengths. This allows other wavelengths to be added in the future to provide new services without disturbing the existing receivers (Clarke and Hoppitt 1990). Upstream voice is handled in the same fashion as described in the TDM system, except that a separate fiber is dedicated for this purpose.

This architecture provides the same service functionality and capacity as the active double star architecture using TDM, while avoiding the deployment of remote electronics in the network. Privacy is still an issue with WDM systems (Wagner and Lemberg 1989). Because the WDM components at the RDU will not separate the signals perfectly, it is conceivable that far-end crosstalk could result in unwanted signals arriving at a subscriber's receiver. Even easier to detect is the reflected light coming off the WDM device from upstream transmissions back to the other subscribers served by the feeder.

Summary

This section presented the alternative optical network architectures in the subscriber loop. The alternatives selected for study provide a range of network services from only narrowband services up to an IBN system that carries a full complement of narrowband, distributed video, and switched video services. In addition, different combinations of transmission technologies have been posited. For each alternative examined in this section, we will construct an engineering cost model to estimate the total investment costs for the architecture.

Figure 3-8. Active Double Star Architecture



4. The Engineering Cost Models

In this section we detail the assumptions of our engineering cost models. We begin with a description of the geographical layout of the network followed by a demand model for broadband services. We conclude with a discussion of cost estimates of key optical and electronic components. In addition, this section examines the technical factors and costs of three network subsystems: the video headend, the electrical power system for the network, and the customer premises equipment (CPE).

Layout of the Network

The engineering cost models focus on the case where all construction takes place in a new, large residential community without any pre-existing telecommunications plant. All construction is below ground, which, when synchronized with the underground plant construction of the streets and sidewalks, results in reduced installation costs. Because buried and underground cable installation are expensive, the approach assumes a one-time installation of network fibers for voice and video to all homes.[10] Once the cable installation crews and equipment have been diverted from a neighborhood, it is prohibitively costly to return to the area for further construction.[11]

The costs of installing fiber cable can vary widely depending upon, among other things, the housing density of the neighborhood. We assume a serving area encompasses a new residential development consisting of a square area containing 25,600 households, 160 homes on a side. To determine the cost of the distribution network, the area is broken down into 25 regions, each containing 1024 households, with 32 homes on a side, uniformly distributed throughout a square grid of blocks with a mean housing density of 88 homes per street mile.[12] The models determine the investment costs for one of these areas serving 1024 subscribers, including the central office and feeder equipment, and installation attributable to the area. The length of the feeder loop is given by a distribution of residential loop lengths taken from a survey of existing Bell telephone networks (Bellcore Technical Reference 1986). As a result, the end of the feeder network (the RDU in an active double star architecture) lies a mean distance of 3072 meters from the central office in the center of the serving area. The cost of RDU equipment can be shared over 1024 subscribers, while headend and central office costs can be shared over 25,600 subscribers.

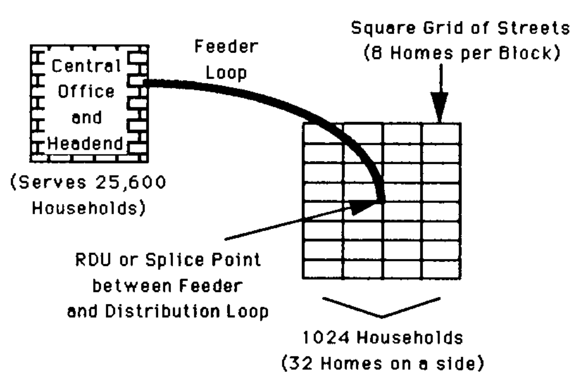
The cable routes in all models follow the same square grid of streets and rights-of-way in the distribution loop of the new serving area. Distribution cables run in conduit under the center of the street, while drop cables run along each side of the street. The overall investment cost is highly sensitive to cable installation costs, which vary widely with local conditions. The installation cost of distribution and drop cable is assumed to be \$4 and \$2 per meter, respectively. Installation of the feeder cable, which runs deeper than distribution cable and passes through existing neighborhoods, costs \$12 per meter (Kerner, Lemberg, et al. 1986).

Finally, to simplify the analysis, the methodology assumes that initial construction includes enough fiber to meet all of the subscriber demand as predicted by the demand model described below. For example, initial deployment of the IBN active double star architecture includes enough feeder fibers to serve a 100% penetration of switched video services. In present value terms, a more cost-effective strategy might be to defer some fiber installation until enough households subscribe to justify the additional investment, even though going back to reinforce the existing fiber will result in higher labor costs than installing it all at once (Reed and Sirbu 1989).[13]

Estimating the Demand for Video Services

Our models assume all households in the service area automatically receive telephone

Figure 4-1. The Network Model



service, but they must choose to sign up for new video services. As they subscribe, the telephone company then installs the necessary electronics throughout the network. The video package gives each subscriber two video channels with which to select either from among 64 distributed video channels (comparable to today's basic, pay, and pay-per-view cable television services) or from switched video offerings. To allow for future growth, the broadband switching electronics provide up to four switched video channels per subscriber and the electronic components that would be needed to transmit the signals (although the equipment at the customer's home is assumed to contain only what is required for two simultaneous channels).

The demand for switched video services determines how much capacity should be installed in the network. Consider the feeder portion of an active double star IBN. At one extreme, if all households watch only the distributed video channels to the exclusion of switched video channels, four feeder fibers capable of carrying 16 video signals each at the STS-3 rate, could provide up to 64 distributed video channels. At the other extreme, if all households simultaneously select a switched program, each would require a dedicated channel in the feeder loop. If the RDU serves 1024 subscribers, an additional 64 feeder fibers (1024/16) would be required for the switched video in addition to the four noted above for the 64 distributive video channels.

The most popular time for television viewing is between 8 p.m. and 11 p.m. each evening. A 1989 Nielsen survey found that an average VCR household spent 3 hours and 45 minutes per week watching video cassette tapes and another 2 hours and 11 minutes recording network television programming (Stewart 1990). Almost 40% of the taping of network programming occurs during prime time and 17% takes place while the television is tuned to another channel. Thus, any estimate of the demand for broadband services by residential subscribers must allow for more than one television in use per household, each tuned to a different program. The demand model described below assumes that second, third, and fourth drops increase the total number of users by 20% over the base number of households subscribed; however, these additional drops generate requests for on-demand service at half the rate of the primary drops.

The demand model estimates the number of channels required for on-demand video employing traditional traffic engineering techniques. The calculations assume a full availability, Erlang B loss system with a 1% grade of service (Schwartz 1987). A key parameter, P, is the percentage of subscribers requesting a channel during the peak busy viewing hour. It is defined by the product of the average hourly video traffic per subscriber per week (A) and the percentage of weekly traffic which occurs during the peak busy hour (p). For example, if the average subscriber views one 90-minute video per week ($A = 1.5$) and 10% of the traffic occurs during the peak busy hour ($p = 0.1$), then the percentage of subscribers during the peak hour is $P = Ap = 0.15$. Alternatively, P could be interpreted as the "viewing share" of on-demand video, reflecting the percentage of all televisions in the area tuning in to on-demand television during the peak hour.[14] In this view, P would have to saturate well below 68%, which is the percentage of households typically viewing television on any given evening (Friedman 1988).

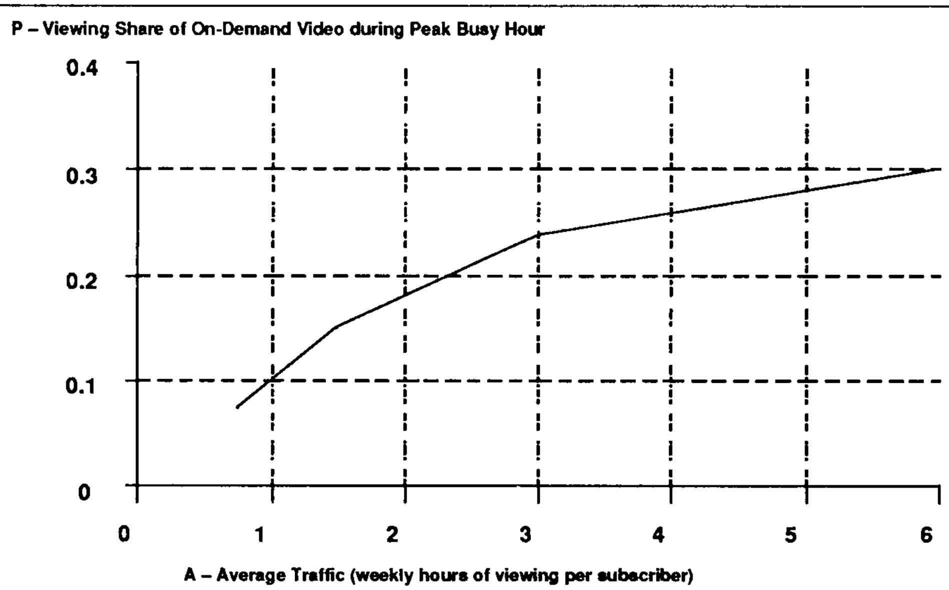
Reflecting the uncertainty in calculating the number of subscribers requesting a switched channel (P), the analysis considers a range of values for A between 45 minutes and 6 hours per subscriber per week. However, one would not expect the relationship between P and A to be linear over the entire range of A. An increase in A reflects multiple viewings of programs spread over the entire week, and as a result the overall percentage of video requests in the busy hour, p, would decrease. Thus, over the range of A assumed to be 0.75, 1.5, 3, and 6 hours per week, P varies in a piece-wise linear fashion equalling .075, 0.15, and 0.24, until saturating at 0.3, respectively, as shown in Figure 4-2.

Passive Double Star. As described earlier, the TDM approach of the passive double star architecture combines 24 STS-1 video signals onto a feeder fiber from the central office. Recognizing that multiple households might desire to watch the same network programming from the same channel, one could calculate how many households h can be served by M channels at some grade of service. However, most television viewers like to scan the available distributive video channels. Since it seems unlikely from a marketing perspective that a system operator can afford to deny customers the right to "spin the dial," there is a reduced opportunity for gain due to call statistics. Thus, if M is the number of channels per fiber, and S is the fraction of additional channels per household which will be viewed concurrently with the primary connection, then $h = M/(1+S)$.

Cost of Network Components

Certainly one of the most difficult tasks in the study has been the effort to obtain

Figure 4-2. Estimated Viewing Share of Switched Video Viewing



reasonable estimates for the costs of network components. While a few cost studies of fiber networks in the subscriber loop have been published, these articles uniformly fail to document adequately the cost assumptions so as to make duplication of their results possible.[15] In fact, as a rule the telephone industry appears reluctant to publish the details of its own cost estimates, holding the view that this economic information is proprietary in nature. From a strategic perspective such a stance is understandable; if a competitive marketplace were to evolve, the telephone companies would not want to have tipped their hand to potential competitors. However, the policy of withholding economic information on proprietary grounds adds to the uncertainty of the policy-making process and leaves telephone company claims vulnerable to skepticism. In any case, the paucity of economic information dictated that cost estimates had to be obtained across a broad range of published sources and interviews with industry experts.

The cost estimates in this study assume key functional components, such as switching and multiplexing, can be implemented as custom-designed integrated circuits. The type of semiconductor technology, hence the cost of the component, depends upon the speed and complexity of the device. High-complexity, low-speed functions require high-density, VLSI integrated circuits such as CMOS circuitry. Currently, manufacturers can mass produce VLSI chips with CMOS technology which consume low power and operate at speeds up to about 200 Mbps (Chao, Robe, et al. 1988). Low complexity, high speed functions (such as multiplexing at the gigabits-per-second rate) require medium scale integration (MSI) integrated circuits using silicon bipolar or gallium arsenide (GaAs) technology. The more costly silicon bipolar and GaAs integrated circuits are less mature than CMOS chips; they consume more power, have lower device densities, and lower production yields.

State of the art transmission technology currently operates around 2.4 Gbps using GaAs integrated circuits. Future applications of sub-micron CMOS technologies could lead to integrated circuits with speeds up to 600 Mbps (Berthold 1990). This implies the cost differential between 600 Mbps and 200 Mbps electronic equipment will not be significant in the future. It is in anticipation of this technological development that the IBN architectures examined in this study assume that subscriber line rates near 600 Mbps are reasonable. Manufacturers can now produce large quantities of custom designed, CMOS devices, at so-called "silicon foundries," for a few dollars apiece.

Within this context, the cost estimates reported below assume widespread introduction of optical components in the 1995 to 2000 time frame which yield further reductions in cost below today's levels. Also, the technical and cost forecasts assume that many network components, such as broadband switching cards and multiplexers, are developed with a high degree of functional integration in the form of VLSI or MSI chip sets as discussed above, which leads to large reductions below today's costs.[16] Table 4-2 lists the estimates of the current and future costs of the network components based on published sources, as noted below, and contacts with manufacturers. A Bellcore study found that the cost of electronic devices increases another 20% to 80% above the base cost — depending upon the nature of the equipment and local conditions — to cover the costs of site engineering, field installation, and acceptance testing (Lu

Table 4-2. Estimated Costs of Network Components (in dollars)

Component	*Current Cost*	*Future Cost*	*Description*
Single-mode Fiber	0.20/meter	0.10/meter	Glass fiber.
Feeder Fiber Sheath	4.0/meter	4.0/meter	Fixed cost of feder fiber cable.
Distribution Sheath	1.0-2.0/meter	1.0-2.0/meter	Fixed cost of 4- to 20-fiber cable.
Feeder Inner Duct	1.15/meter	1.15/meter	Not including installation.
STS-12 Transmitter	300	60	LED or Laser Diode.
STS-48 Transmitter	2500	200	Laser Diode.
STS-12 Receiver	150	40	PIN photodiode.
STS-48 Receiver	1500	120	PIN photodiode or APD.
Analog Transmitter	5000	400	DFB Laser.
Broadband Switching Card	NA	200	64x64 video switching card without software.
Digital Loop Carrier	18,600 + 130/line	8000 + 55/line	Multiplexing and routing system costs at the RDU.
STS-48 Multiplexer	NA	2240	Multiplexing 16 STS-3 channels.
SONET Chip	100	25	STS-12 framining and routing.
Video Modulator	800-2000	100	Low-quality modulator.
Video Codec	NA	80	STS-3 digital/analog converter.
CEV	60,000	60,000	Controlled environment vault.
Power Splitter	80	25	Cost per port of power splitter.
Connector	75	25	Single-mode installed.
Splice	40	15	Cost per splice, including lobor.
WDM	100/port	35/port	Wavelength Division Multiplexer.
Fiber, pigtail, panels, shelves	250/fiber	75/fiber	Cable distribution management – pigtail (50), panel (25).
Copper Twisted Wire Pairs	0.033 – 0.018/pair	0.033 – 0.018/pair	
Protective Block	30	30	Grounded block for two lines.

NOTE: NA means equipment not currently available or cost unknown.

and Wolff 1988). Accordingly, the costs of the electronic devices in Table 4-2 are marked up another 40% to reflect these factors.

Power Issues in the Subscriber Loop

The cost of power processing and distribution for a residential fiber network is likely to account for a sizable portion of the overall investment. Metallic transmission media can generally carry enough electrical power to run network and CPE components, but optical fiber cannot carry power. Moreover, because of network synchronization and performance requirements, network equipment will need to draw power continuously, not only when the circuit is used, as is the case with copper. New arrangements will be needed to power the active components throughout the network. Power considerations are given credit for redirecting research attention away from the active double star architecture to passive photonic loop architectures that reduce the powering requirements of the network (Chynoweth 1988).

General Considerations. The "worth of a watt" is the net present value of energy and equipment costs associated with each watt of power consumption (Goldstein, Jacobs, et al. 1978). This value is also the maximum sum that should be spent today on more energy efficient equipment for each watt of power saved. The worth of a watt reflects the capital costs of power for distribution, rectification, conversion, batteries, engines and air conditioning equipment, as well as capital equivalent costs such as the cost of energy consumption, energy expended during power processing, distribution and air conditioning, and maintenance.

Over a 30-year study period, (Goldstein, Jacobs, et al. 1978) estimated the worth of a watt at the output of a central office serving copper lines to be about $20. Mistry, Taylor, et al., (1989) estimated the worth of a watt to be roughly $25 at the remote distribution unit of a DLC system, and an astounding $165 per watt for a fiber network extending all the way to the home. If the customer interface were to consume as much as 5 to 10 watts for broadband service (Chynoweth 1988), power system costs alone might have a present value of between $825 to $1650 over a 30-year period — almost the installed first cost of the fiber network itself.

However, there are reasons to believe that advances in technology will lead to power system costs reduced below those reported by Mistry. As is consistent with the treatment of technology advances in other areas, our estimates are optimistic with regard to reduced power consumption or cost.

Fiber to the Home. The active double star architecture requires power at the central office, RDU, and ONI. The switched star and passive architectures bypass the need for power at the RDU. For the all-fiber networks, the models assume the cost of power per watt at the central office and remote distribution unit is the same as for DLC systems — the only difference being that more power may be needed to handle broadband signal processing.

The all-fiber models assume the ONI is located on the subscriber's premises and powered locally with backup power provided from the curb. AC power could be tapped directly from an AC utility pole, but the models assume a ring adapter is connected to the customer's energy meter, along with the wiring from the outlet to the ONI power supply. This alternative is the most likely for the following reasons:

- The telephone company continues to be responsible for backup power, thereby maintaining a high level of network reliability and not subjecting the subscriber to new, unwanted, responsibilities;
- The pedestal provides a degree of sharing of power resources;
- The potential would exist to colocate the ONI with the power supply, at the pedestal, to form a fiber-to-the-curb architecture.[17]

The capital costs of powering the ONI have several components (Mistry, Taylor, et al. 1989). The models assume the capital cost for this option to be about $50 per watt. Table 4-3 illustrates how this figure is determined. The calculations are based on the assumptions that each pedestal connects to eight subscribers and the efficiency of the power supply is 90% (Sugiura, Ogata, et al. 1988).

Table 4-3. Capital Costs of Power System to the Optical Network Interface (in dollars)

Power System Component	*Cost/Watt Per Subscriber*	*Description*
Power Transformer	6.9	Cost of $50 per watt shared over the number of subscribers per pedestal assuming a 90% power efficiency [(50/8) x (1/0.9)].
Eight-hour Battery Back-up	8.9	Batteries cost $1/watt-hour assuming a ten year lifetime and 90% power efficency [(8x1) x (1/0.9)].
Battery Charger	5.0	Constant voltage charger to maintain batteries.
ONI Converter	5.0	
Power Drop Wire	5.0	Use the copper pair for power delivery.
Utility Power Connection	18.7	Connection from utility pole to the pedestal – shared over the number of subscribers per pedestal (150/8).
Total	49.5	Total capital costs per line per watt for local power at the ONI with back-up power from the curb.

The Cost of Powering Alternative Network Architectures. Table 4-4 lists the capital costs of network power for the various network architectures assuming per watt costs of $10 in the central office, $15 in the remote distribution unit, and $50 in the ONI. The analysis assumes the ONI consumes between two watts of continuous power if configured for narrowband services only (Coleman 1990) and up to seven watts in some IBN configurations (Chynoweth 1988).

Table 4-4.
Investment Cost Per Home Passed of Power Systems with Alternative Network Architectures (in dollars)

	Level of Network Service			Cost by Network Location (Watt/Line)			
Network Alternatives	*Narrowband*	*Cable*	*Switched Viceo*	*Central Office $10/watt*	*Remote Node $15/watt*	*ONI $50/watt*	*Overall Total*
Active Double Star Architecture							
Digital Loop Carrier	•			1	36		37
Fiber Narrowband	•			1	45	150	196
Voice and Cable	•	•		1	60	250	311
IBN	•	•	•	2	75	300	377
Passive Star Architecture							
Fiber-to-the-Curb	•			1		150	151
Fiber Narrowband	•			1		150	151
IBN (STS-1/Home)				20		300	320
IBN (STS-3/Home)	•	•	•	25		350	375
Switched Star Architecture							
IBN	•	•	•	40		300	340

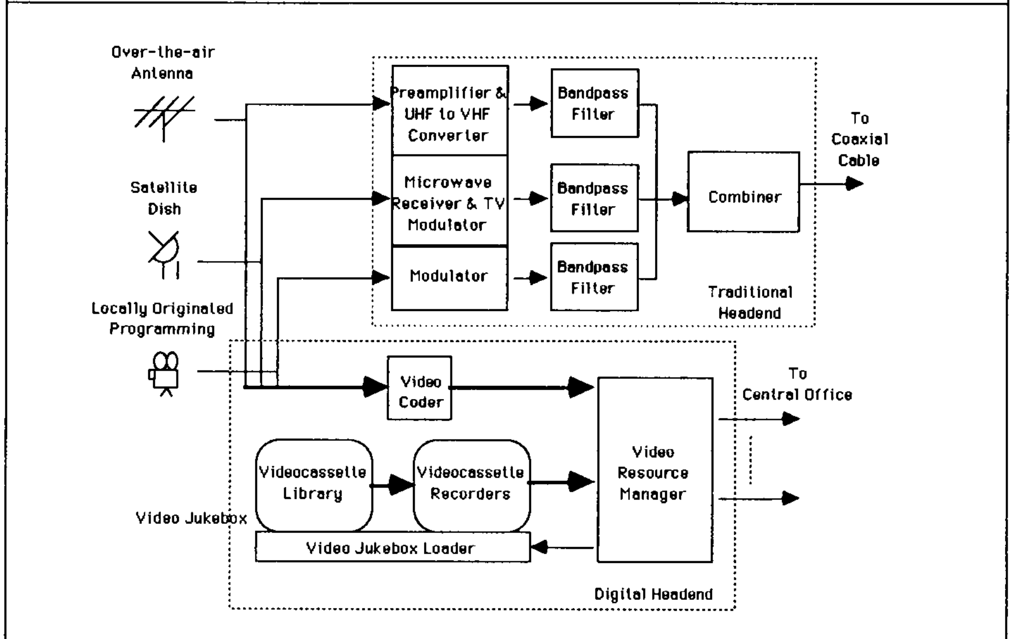
Video Headend and Jukebox

Up to this point, the focus has been on the network architectures and equipment used in the subscriber loop. However, provisions must be made for feeding the broadband services, especially entertainment video, into the subscriber loop network. This section provides an estimate of the costs for a headend equipped with a jukebox capable of offering switched video services. All the engineering planning models include the video headend and jukebox in the calculations of total costs whenever video services are offered. Headend costs are shared over all 25,600 households located within the central office serving area.

Figure 4-4 shows a block diagram of the headend equipment required to deliver a full complement of both traditional cable services (all models assume the headend delivers 64 channels of distributed video) and on-demand video service using a video jukebox (Judice, Addeo, et al. 1986; Webb 1983).

Headend Costs for Switched Video Equipment. A true on-demand video service requires the customer's request for a specific program to be promptly satisfied. The requested program has to be retrieved from a video library and loaded into some type

Figure 4-4. Block Diagram of a Cable Television Headend with Video Jukebox



of video disk or cassette player. Automated jukeboxes are not without precedent.[18] Accordingly, the headend model assumes a jukebox capable of accessing over 6000 programs at a cost of $800,000.

Table 4-5 shows total costs with and without the video jukebox. The figures depend on the assumed penetration rate of the video services and the hourly average of weekly traffic offered per subscriber for switched video services. The total cost of the jukebox per video subscriber is $122, assuming 60% penetration of video services and 1.5 hours of weekly viewing of switched video. Overall, the headend cost is $138 per video subscriber for distributive and switched video services, assuming a digital transmission format.

Subscriber Premises Equipment

Deploying fiber to the home requires the placement of new ONI equipment on the subscriber premises. Table 4-6 lists the components of the ONI needed to serve individual residences with a minimum of N-ISDN phone service. Table 4-6 also shows the estimated cost of the narrowband and broadband CPE. The active double star and passive double star architectures require slightly different CPE. For narrowband service alone, the CPE costs $167 and $182 for these two architectures, respectively. In contrast, using copper in the drop loop would eliminate the need to convert the optical

Table 4-5. Headend Costs with 60% Video Penetration (in dollars)

Headend Component	Single Item Cost	Total Cost	Description
	Distributed Video Equipment		
Tower and Building	35,000	35,000	
Outside Receivers	30,000	30,000	Earth station, over-the-air antenna
Microwave Antenna	15,000	15,000	
FM Receivers	5,000	5,000	
Standby Power	9,000	9,000	
Microwave Receiver	4,500 per channel	144,000	Assume 32 out of the 64 channels are received by microwave or satellite dish: 32x4500
Video Codec	80 per channel	5,120	For all 64 channels: 64x80
	Total	243,120	$9.5 per home passed at 60% penetration: 243,120 + 25,600
	Video Jukebox Equipment		
Video Jukebox	800,000	800,000	
Video Library	5/cassette	88,250	17,650 cassettes assuming 1.5 hours of weekly viewing: 17,650x5
Video Player	200 per player	600,000	3000 players required for 1.5 hours of weekly viewing: 200x3000
Video Codec	80 per channel	240,000	Codec per channel: 3000x80
	Total	1,728,250	$67.5 per home passed at 60%penetration: 1,728,250 + 25,600
Overall Total		1,971,370	$77 per home passed at 60% penetration

signal to an electrical signal (or vice versa) in the CPE. The only cost component necessary is for the grounded lightning protection block at $30. Broadband PONs presume more expensive compression of video signals in order to permit more subscribers to be served per fiber. This leads to a higher cost for CPE.

Table 4-6. Cost of Customer Premises Equipment

Item	Star & Active Double Star	Passive Double Star	Comments
Narrowband Components			
Optical source	60	60	Light Emitting Diode.
Optical receiver	40	40	PIN photodiode.
ISDN chip	15	15	Includes BORSHT functions.
Timing chip		15	Ranging protocol chip of upstream voice signal.
D-A converter	7	7	Digital-to-analog converter.
WDM	35	35	Wavelength division multiplexer.
CPE cabinet	10	10	Installed outside of premises.
Total	**167**	**182**	
Broadband Components			
Multiplexer	35	25	Multiplexing functions of the N-ISDN and video signals.
Video codec	80	80	Codec for one channel.
Video coder		40	Decompresses video signal.
Cost of second drop	16	24	Assume 20% of subscribers request second video channel.
Total	**298**	**351**	

5. Results

This section describes the results of our engineering cost models which forecast the investment costs required to construct a fiber network in residential areas.[19] The models allow us to examine the economic viability of the network alternatives. Knowledge of the cost functions make it possible to predict which network services and architectures a company might choose to build. We do not consider any video programming, network operations, or maintenance expenses.

Network Investment Costs

The engineering cost models calculate the *cost per home passed* by dividing the total cost by the total potential subscriber population (the number of residences in the neighborhood). Another measure could be the average cost per subscriber, found by dividing the total cost by the number of subscribers requesting a particular service. This study consistently reports cost per home passed to avoid any confusion regarding the denominator in an average cost per subscriber calculation. However, one must carefully consider the cost per home passed measure. By averaging the costs over all the households, instead of only that percentage of households requesting a particular service, this measure can appear to incorrectly attribute costs to households not subscribing to all services.

For example, if the LEC were to replace perfectly functioning copper plant with fiber plant, any additional cost due to the new fiber network should be borne strictly by those demanding the new network capabilities. Telephone subscribers should not have to pay any more for telephone service over a fiber network than they would otherwise pay with a separate copper network. It may very well be that a portion of the additional capital costs for fiber should be properly attributed to telephone subscribers, a portion equal to the present value of any savings in operations and maintenance expenses arising from the switch from copper to fiber. If these savings do not offset the higher capital costs, then the fiber network is not a cost-efficient means to provide telephone service and would result in higher than necessary telephone rates. Thus, as will be seen below, when the methodology requires that all costs be fully attributed to one service, the conversion to average cost per subscriber is made for the calculation.[20]

Estimated Costs of Narrowband Networks

Given the current regulatory restrictions and uncertainty regarding broadband ventures, the LEC might want to first build a network with fiber optics that continues to provide only narrowband services similar to today's offerings. This analysis considers several narrowband alternatives ranging from the DLC system with fiber in the feeder link, to systems extending fiber all the way to the home.

Table 5-1 shows the *current* estimated costs of the narrowband alternatives. These figures demonstrate the current, high cost of network components in optical transmission systems relative to copper; large differences arise in the cost of the RDU, the distribution loop, and the CPE. The DLC system, with fiber only in the feeder network, is clearly the lowest cost architecture at $920 per home passed. This compares to the hybrid fiber/copper architectures, which run fiber to the pedestal at a cost of $1675 per home passed, and the lowest-cost fiber-to-the-home alternative at nearly $1925 per home passed. The all-fiber, active double star architecture is particularly costly at $2948 per home passed as a result of the high current cost of optical components and electronics devices. The CPE component of the all-fiber alternatives illustrates the high costs of placing the ONI near the home. Conventional telephone service in the DLC or hybrid systems involves no special CPE in the home.

The *future* (5 to 10 years) estimated costs of the narrowband networks predict a smaller gap between the costs of the DLC system and the other alternatives, and in particular the passive optical network systems (see Table 5-2). While the cost of a DLC system is forecast to decrease about 25% to $696 per home passed, the cost of a hybrid bus architecture falls over 50% to $772 per home passed. The larger decrease in hybrid system costs arises because the network contains more optical transmission components whose costs are expected to decline significantly in the future. In spite of this, the all-fiber architectures remain much higher in cost than the DLC or hybrid alternatives, with the cost of the passive triple star notably less than the active double star network. In general, these results indicate that the use of fiber, even in narrowband networks alone, will reduce the costs of *local* telephone service in the future as lower cost optical components, mainly in the feeder lines, become available.

So what do these results suggest a LEC might do over the next decade given this new construction scenario? There are two possibilities. First, if the firm believes it will be indefinitely constrained to carrying only narrowband services, then the rational firm would choose not to build an all-fiber narrowband network (unless the present value of operations and maintenance savings could offset the difference in capital costs). Instead the firm would install DLC systems now, and consider DLC and hybrid systems for the future.

The second possibility occurs if the telephone company expects to enter broadband markets in the future. Now the issue of network evolution becomes more complex. The firm will plan its investment strategy based not only on the anticipated demands for narrowband services, but for the broadband services it wants to provide as well. Again hybrid systems are attractive because they put a potential broadband link close to the home. All-fiber narrowband networks position a potential broadband link all the way to the home. In both cases, the network architecture and the costs of components constrain the capacity the network can offer each subscriber. Within its physical lifetime, the all-fiber network might serve as the foundation to support any combination of future services. As a result, a LEC could decide that the present value of the all-fiber network — in consideration of the expected revenues, capital, operation and maintenance expenses, plus the flexibility to offer new broadband services rapidly as the markets evolve — justifies the added expense (an increase in first costs of $175 per home over the hybrid bus architecture). The LEC would then choose to go ahead with an all-fiber network in spite of the costs. Such an action raises several serious public policy issues, the discussion of which we defer until the next section.

Finally, how do our cost estimates of the DLC system compare to other estimates of today's DLC systems? As might be expected, estimates for the cost of DLC systems or other copper-based approaches are sketchy. A recent Bellcore article *asserts* that the cost of providing DLC is *as much as* $1500 per new installation, and an average of $900 for all types of new copper-based installations (presumably, this aggregate figure reflects an average of simple copper star networks for short loop lengths and DLC systems for longer loop lengths) (Shumate 1990). A study by AT&T reports the installed first cost for copper distribution media is about $500 for a route length per living unit of 18 meters (the route length is the total cable trench length divided by the number of living units) (Ensdorf, Kowal, et al. 1988). This corresponds roughly to the route length in our DLC model at a cost of $407 in the distribution and drop network. The lower costs in this study may be due to the assumed new construction scenario, which reduces significantly the cost of cable installations and trenching. It is also possible we have underestimated engineering and planning overhead.

Estimated Costs of Distributed Video Alternatives

The results in the previous section imply that the more fiber included in the network, the higher network costs should climb. For the LEC, this suggests an investment strategy of laying fiber progressively closer to the home only as advances in technology decrease the costs of optical components enough to justify new construction. An important factor in such a strategy is the amount of fiber capacity pre-installed along each link to handle future services. The fiber capacity in the network determines how easily the architecture can be upgraded to deliver broadband services. For example, while it appears inefficient to install all-fiber double star networks for narrowband services alone, the systems do provide the infrastructure to support future network evolution to broadband services. In contrast, hybrid systems may be more difficult to upgrade. Barring another round of fiber installation, these architectures are likely to require significant advances in WDM or coherent transmission techniques to carry broadband services.

We turn now to the costs to a LEC of building residential networks carrying narrowband services *in combination with* distributed video. Table 5-3 lists the estimated *future* costs for these systems. The passive hybrid systems are the lowest cost, integrated services alternatives. The future costs of the hybrid double star and bus architectures are $1242 and $1222 per home passed, or $463 and $450 above the cost of their respective narrowband counterparts. The future cost of the all-fiber, active double star architecture remains high at $1684 per home passed, even though this is only $289 above its narrowband counterpart. The active double star topology pre-installs enough capacity in the distribution network to carry an integrated mix of narrowband and broadband services without the need for new capacity. As a result, the upgrade to broadband services consists of adding electronics to the central office, RDU and customer premises, in addition to reinforcing the feeder network. Curiously, the all-fiber passive double star network is now the highest cost alternative. Because it is infeasible to transmit simultaneously all 64 distributed video channels to each subscriber, this alternative must give each subscriber the ability to select one video channel from the central office. In effect, this is switched video capability to provide distributive video channels, and explains the added expense.

If a network is installed which provides services A, B, and C, then the *upgrade* cost is the additional investment to retrofit the network to carry service D. The *incremental* cost of service D is the difference in installed first cost between a network providing services A, B, C and D and one providing only A, B and C. The upgrade cost is always greater than the incremental cost because retrofitting may require scrapping existing equipment and incurring additional installation costs. Clearly, for a given architecture,

Table 5-1.
Estimated Current Cost Per Home Passed of Alternatives Providing Only Narrowband Services (in dollars)

Network Alternatives	*Central Office*	*Feeder Network*	*ONI (RDU/ Pedestal)*	*Distrib. Loop*	*Drop Loop*	*Customer Premises*	*Total Cost*
Active Double Star Architecture							
Digital Loop Carrier	17	49	447	175	106	126	920
All-Fiber Narrowband	17	49	1165	640	295	782	2948
Passive Star Architecture							
Hybrid Double Star	104	146	1043	212	106	90	1701
Hybrid Bus	101	155	1050	158	106	90	1660
All-Fiber Triple Star	130	95	50	504	295	860	1934

the closer the upgrade cost is to the incremental cost, the easier it is to contemplate a phased investment strategy. In general, hybrid architectures suffer from a divergence between incremental and upgrade costs.

Estimated Costs of Switched Video Alternative

The estimated future costs of the switched video alternatives are shown in Table 5-4. We report cost per home passed results based upon variable costs calculated assuming 60% penetration of video services and 1.5 hours of weekly on-demand video viewing per subscriber. The passive double star architecture (STS-1 channel per subscriber) shows large savings by eliminating electronics and sharing plant in the distribution loop, resulting in the lowest cost option at $1898 per home passed. High broadband electronics costs, however, increase the cost of this architecture to $2140 if each subscriber receives an STS-3 signal. Savings in feeder plant are sufficient to make the

Table 5-2.
Estimated Future Cost Per Home Passed of Alternatives Providing Only Narrowband Services (in dollars)

Network Alternatives	*Central Office*	*Feeder Network*	*ONI (RDU/ Pedestal)*	*Distrib. Loop*	*Drop Loop*	*Customer Premises*	*Total Cost*
Active Double Star Architecture							
Digital Loop Carrier	3	46	240	175	106	126	696
All-Fiber Narrowband	2	46	415	356	209	367	1395
Passive Star Architecture							
Hybrid Double Star	16	88	300	179	106	90	779
Hybrid Bus	15	104	307	150	106	90	772
All-Fiber Triple Star	19	71	16	250	209	382	947

Table 5-3.
Estimated Future Cost Per Home Passed of Alternatives Providing Distributed Video Services Assuming 60% Penetration of Video Service (in dollars)

Network Alternatives	*Central Office*	*Feeder / Trunk*	*RDU or ONI*	*Distrib. Loop*	*Drop Loop*	*Customer Premises*	*Total Cost*
Active Double Star Architecture •							
All-Fiber	45	53	396	356	208	626	1684
Passive Star Architecture •							
Hybrid Double Star	48	153	438	208	197	198	1242
Hybrid Bus	47	140	432	190	215	198	1222
All-Fiber	314	221	91	252	290	663	1831

• *Estimate includes costs of providing narrowband services*

active double star network the lowest-cost alternative at $2004 per home passed for carrying STS-3 channels to the subscriber. Both the passive double star using WDM ($2429) and the switched star ($2531) architectures are significantly higher in cost. The high costs of these alternatives arise because each subscriber requires a high degree of dedicated equipment, for switched services.

Large fixed costs, if they exist, lead to an average cost function which depends strongly upon the penetration rate. Figure 5-1 confirms this observation for the switched star, active double star, and passive double star (STS-1 channel per subscriber) alternatives. The figure plots the average cost per video subscriber (to both distributed

Table 5-4.
Estimated Future Cost Per Home Passed of Switched Video Alternatives Assuming 60% Penetration of Video Service and Average On-Demand Video Viewing of 1.5 Hours per Week (in dollars)

Network Alternatives	*Central Office •*	*Feeder / Trunk*	*RDU or ONI*	*Distrib. Loop*	*Drop Loop*	*Customer Premises*	*Total Cost*
Integrated Broadband Network Architecture ∗							
Switched Star	455	887	91	264	208	626	2531
Active Double Star	221	70	523	356	208	626	2004
PDS (STS-1/Home)	381	221	91	252	290	663	1898
PDS (STS-3/Home)	631	150	91	250	219	799	2140
Passive Double Star-WDM	874	150	91	382	269	663	2429

• *Central Office figures include headend and jukebox costs (see Table 4-5)*
∗ *IBNs carry narrowband services, plus swithced and distributed video services*
PDS-Passive Double Star; WDM-Wavelength Division Multiplexing;
SCM-Subcarrier Multiplexing; TDM-Time Division Multiplexing

video and switched video services) against the fractional penetration assuming 1.5 hours of weekly switched video usage per subscriber. The average cost figures emphasize the high cost of switched video networks if there is an insufficient interest or intense competition in broadband service markets resulting in low video penetration rates. The cost function of the passive double star (STS-1 channel per subscriber) architecture exhibits increasing average costs at very high penetration levels (above 90%). At this high level, the increasing results do not influence the analysis of market structure (i.e., they do not suggest it is profitable for a second firm to enter the market). This upswing is due to the costs of installing additional equipment to satisfy the second channel requests of the subscribers.

The large amount of fiber in the all-fiber networks make the total cost sensitive to variations in the price of fiber. Table 5-5 shows the totals with the cost of fiber at $0.5, $0.10 and $0.20 per meter. The final column of the table is the percent age decline in total costs when the cost of fiber falls from $0.20 to $0.5 per meter. Those alternatives with a higher proportion of fiber in the network are most sensitive — witness the 24% cost decrease of the switched star. Somewhat surprising is that the active and passive double star networks show similar declines. The apparent contradiction — passive optical networks, after all, are supposed to significantly decrease the amount of fiber by sharing — suggests the proportion of fiber to other network plant is roughly equivalent, and raises an interesting point regarding the location of shared fiber. The passive double star requires more feeder fibers and less distribution fibers relative to the active double star. The higher degree of sharing in the distribution network, located closer to the subscriber and therefore more dedicated in nature, partially explains the lower cost of this architecture.

The cost estimates reflect a host of assumptions regarding the future costs of electronics components as discussed in Section 4. How might total costs vary if these estimates prove to be overly optimistic or conservative? Table 5-6 investigates the

Figure 5-1.
Average Cost Per Video Subscriber of IBN Architectures
Assuming 1.5 Hours of On-Demand Video Viewing Per Week (in Dollars)

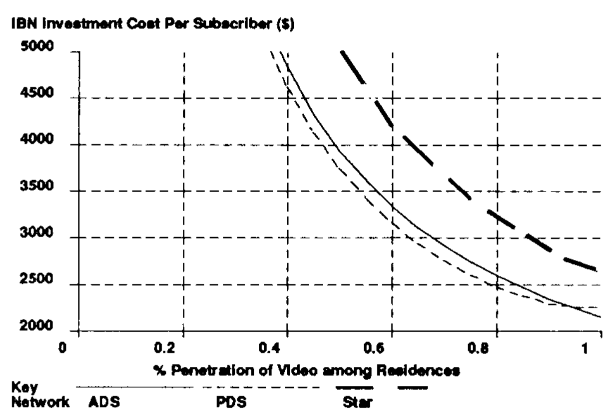


Table 5-5.
Variation in the Estimated Future Cost Per Home Passed of IBN Alternatives to the Price of Fiber Assuming 60% Penetration of Vido Service and Average On-Demand Video Viewing of 1.5 Hours Per Week (in dollars)

Network Alternatives	*Cost of Single Mode Fiber*			*Percent Decrease*
	0.20/meter	*0.10/meter*	*0.05/meter*	
Integrated Broadband Network Architectures				
Switched Star	3017	2531	2288	24
Active Double Star	2115	2004	1949	8
Passive Double Star (STS-1/Household)	1819	1898	2056	11
Passive Double Star (STS-3/Household)	2079	2140	2262	8
Passive Double Star-WDM	2551	2429	2368	7

Table 5-6.
Variation in the Estimated Future Cost Per Home Passed of IBN Alternatives to Electronic Costs Assuming 60% Penetration of Video Service and Average Weekly Viewing of 1.5 Hours (in dollars)

Network Alternatives	*Variation in Electronics Costs*			*Percent Increase (High / Low)*
	Low	*Base Case*	*High*	
Integrated Broadband Network Architectures				
Switched Star	2412	2531	2769	15
Active Double Star	1788	2004	2435	36
Passive Double Star (STS-1/Household)	1806	1898	2083	15
Passive Double Star (STS-3/Household)	1925	2140	2569	33
Passive Double Star-WDM	2068	2429	3151	52

sensitivity of the total cost per home passed to the estimated electronics costs. The "High" and "Low" columns assume electronics components are 150% or 50%, respectively, of their base case costs. The final column shows overall costs vary between 15% to 52%. The wide variation in total costs reinforces the significance of the uncertainty regarding future electronics costs. Within this environment of high uncertainty the best the analysis can do is recognize its existence, especially when formulating any conclusions based on the results.[21]

A final key uncertainty relates to the cost of powering the fiber-based networks. As discussed earlier, this is a far more important aspect than one might expect because these costs could be very high. The cost estimates of the alternatives include an investment cost of more than $300 per home passed for the power systems and emergency backup batteries. Even though this appears high, it is lower than other estimates (Mistry, Taylor, et al. 1989). However, ever-increasing engineering research efforts into the

Table 5-7.
Variation in the Estimated Future Cost Per Home Passed of IBN Alternatives to Electronic Costs Assuming 60% Penetration of Video Service and Average Weekly Viewing of 1.5 Hours (in dollars)

Network Alternatives	*Percent Decline in Power Costs*			*Percent Sensitivity*
	66%	*33%*	*Base Case*	*(66% of Base Case)*
Integrated Broadband Network Architectures				
Switched Star	2305	2418	2531	9
Active Double Star	1753	1878	2004	13
Passive Double Star (STS-1/Household)	1685	1792	1898	11
Passive Double Star (STS-3/Household)	1890	2015	2140	12
Passive Double Star-WDM	2209	2319	2429	9

Table 5-8.
Estimated Future Cost Per Home Passed of Integrated Broadband Network Alternatives Assuming 60% Penetration of Video Service (in dollars)

Network Alternatives	*Average Weekly Viewing Hours*				*Incremental Cost Per Viewing Hour*
	0.75	*1.5*	*3*	*6*	
Integrated Broadband Network Architectures					
Switched Star	2516	2531	2549	2561	9
Active Double Star	1969	2004	2049	2110	27
Passive Double Star (STS-1/Home)	1883	1898	1916	1928	9
Passive Double Star (STS-3/Home)	2124	2140	2157	2169	9
Passive Double Star-WDM	2413	2429	2446	2458	9

power problem might yield technological advances or new power alternatives with lower costs than estimated in this study. To examine this possibility, Table 5-7 shows the results for power cost reductions of 33% and 66% below the assumed levels. The IBN alternatives are more than twice as sensitive to the cost of network power than fiber backbone approaches. In fact, most of the alternatives are sensitive to these costs because of the potentially high costs of either powering the ONI at the home or providing backup power for telephone service.

Alternatively, the decline in power cost shown in Table 5-7 could represent reductions in the power consumption levels of the network equipment. For example, the ONI at the home in the active double star architecture consumes six watts of power at an assumed cost of \$50 per watt. A 66% decline then corresponds to two watts of power at the ONI.

Table 5-9.
Viewing Shares for Three On-Demand Video Viewing Pattern Scenarios

Scenario	*Average Weekly Viewing Hours*			
	0.75	*1.5*	*3*	*6*
Low	0.0375	0.075	0.12	0.15
Base Case	0.0750	0.150	0.24	0.30
High	0.1500	0.300	0.45	0.48

Table 5-10.
Sensitivity of Estimated Future Cost Per Home Passed of IBNs to Alternative Peak Loading Assuming 60% Penetration of Video Service (in dollars)

Network Alternatives	Alternate Viewing Patterns (1.5 Hours/Week)			Incremental Cost Per Viewing Hour		
	Low	*Base*	*High*	*Low*	*Base*	*High*
Integrated Broadband Network Architectures						
Switched Star	2516	2531	2561	4	9	12
Active Double Star	1969	2004	2110	11	27	36
Passive Double Star (STS-1/Home)	1883	1898	1928	4	9	12
Passive Double Star (STS-3/Home)	2124	2140	2169	4	9	12
Passive Double Star-WDM	2413	2429	2458	4	9	12

Incremental Capital Costs of Switched Video. The models can calculate the incremental cost of offering switched video services. The demand model described earlier calculates the number of video channels needed to satisfy a range of on-demand video traffic estimates at a 0.01 grade of service. Table 5-8 shows the variation in total cost to demand assumptions ranging from a weekly average of 0.75 hours to 6 hours of viewing per subscriber. The final column lists the incremental cost of switched video *per viewing hour per week.* This value is the difference in total cost at two levels of weekly viewing, divided by the difference in the corresponding weekly viewing values. Take the example of the active double star network. The difference in total cost is $141 between the average traffic values of 0.75 and 6 hours per week; dividing $141 by 5.25 (the difference between 0.75 and 6 hours) gives an incremental cost of $27 per on-demand viewing hour per week. The results demonstrate how the total costs of the alternatives are generally insensitive to demand variations for switched video because much of the fiber capacity is already pre-installed to handle future growth in traffic.

How will costs vary if the subscriber viewing patterns differ from those assumed in the demand model? A larger viewing share or peak-hour demand for switched video requires more network capacity to handle the demand, more dispersed viewing means less need for switched video capacity. To examine the sensitivity of total costs to the peak hourly viewing share of on-demand video service, we consider two scenarios which assume viewing shares below ("Low") and above ("High") the base case. Table 5-9 lists the assumptions regarding viewing share versus the average weekly viewing hours per subscriber for these three scenarios. The results for these scenarios are shown in Table 5-10, including the incremental cost per hour of switched video. The cost of the active double star architecture is the most sensitive to subscriber viewing patterns, reflecting the installation costs of additional fiber capacity in the feeder network as demand warrants.

6. Conclusions

There are a number of conclusions to be drawn from this preliminary analysis of fiber optic residential subscriber networks. First, it is clear that running fiber to the home, even assuming significant future reductions in component costs, is likely to remain more expensive than copper, where current loop plant costs are roughly $920 per subscriber. To realize the introduction of a fiber IBN, it must be justified on the basis of additional revenue producing services, such as the delivery of entertainment video.

Second, even without building hybrid or all-fiber networks, the cost of constructing new local telephone service plant using an optical DLC system will decrease due to the falling cost of fiber and other electronic components.

Third, the analysis suggests that a fiber optic network capable of providing both voice and video services to the home can be constructed for $1800 to $2500 per home passed. The cost per subscriber is in the range of the combined cost of a CATV and telephone network only if fiber-based services realize near universal penetration (greater than 85%).

Fourth, all the estimated cost functions appear to demonstrate economies of scale — the average cost functions decrease with increasing subscriber penetration. In a multiproduct environment, however, this is not sufficient to indicate a natural monopoly, which requires the presence of economies of scope.

Fifth, the estimated costs of the alternatives are sensitive to the cost estimates of the electronic components and the powering systems, and relatively insensitive to variations in the price of optical fiber. Thus, future developments in microelectronics, lasers, photodetectors, and powering architectures will greatly influence the economics of network evolution.

Sixth, with respect to alternative architectures, some form of double star, whether passive or active, seems preferable to a single star on the basis of fiber cost savings. At the same time, total costs are more sensitive to variations in subscriber density or installation costs than to fiber cost. It is still too early, given the rapid pace of development in electro-optical technology, to determine a single optimum architecture.

With respect to the active versus passive double star architectures, the cost of the active double star architecture is bracketed by the costs of passive double star systems with 50 Mbps and 150 Mbps video channels respectively. Improvements in compression technology will make the passive systems even more attractive. The passive systems are also likely to enjoy lower maintenance costs. At the same time, improvements in electronics costs will benefit the active double star architecture more than the PON. (If we have underestimated the electronics costs, the sensitivity becomes a liability rather than advantage.) None of our models include the equipment necessary for upstream video; however, a preliminary examination suggests that it will be far more difficult to upgrade a passive star architecture to support upstream video (e.g., for video telephony) than to upgrade the single or double switched star configurations. Finally, the passive double star has a potential privacy problem since the signals for several households are carried on the fiber coming into each home. These signals are demultiplexed in the network circuit terminating equipment (NCTE) and only the signal destined for the particular home is passed to the codec. Security would be less of a problem, though by no means eliminated as an issue, if the NCTE could be treated as carrier rather than customer equipment, allowing the carrier to guarantee its integrity. Such a designation runs against current trends in FCC rulemaking (FCC 1983).

Seventh, the estimated future costs of the WDM alternative suggest this option will be too expensive for the time period of this study, although it still represents an attractive upgrade strategy for the bus and passive double star architectures.

Finally, significant cost savings can be achieved by combining fiber with copper in a hybrid architecture, as part of a strategy of gradual introduction of more fiber into the subscriber loop.

Policy Implications

These engineering and economic conclusions have a number of policy implications.

If the success of an IBN requires revenues from the carriage of entertainment video, then one would expect intense lobbying from the local exchange carriers (LECs) to ease the restrictions which currently block their entry into this market. The FCC has already recommended that Congress ease the cross-ownership restrictions imposed by the Cable Act of 1984. The entry by the LECs into video carriage will raise again the question of whether video signal distributors should be treated as publishers or as common carriers (de Sola Pool 1983). The LECs have been lobbying heavily to have the MFJ's restrictions on content origination lifted so that they might participate more fully in the information services marketplace. However, a LEC freed from the need to separate carriage from content would be much more threatening if it was then allowed to become the monopoly provider of wired video to the home. The LECs may well need to choose between government approval to become the monopoly supplier of wired video to the home, and freedom to originate content on their networks. They are unlikely to receive approval for both.

Second, the high ratio of fixed to variable costs poses a problem in terms of accounting for investments in, and pricing of services provided by, an IBN. Given the relatively high ratio of fixed to variable costs for an IBN, there is a risk that LECs will invest in fiber installation, only to find that penetration remains stalled at 20% or 30%. Under such circumstances, they may attempt to distribute the costs of such investment over all local telephone ratepayers, including those who subscribe only to more traditional narrowband services.

Whether or not this is a desirable policy is certainly open to debate. Some would argue that it is an appropriate way to encourage the introduction of new technology which will ultimately become universal. Others might take the position that only subscribers of the new fiber-based services should bear the costs of fiber installation. If the latter view is taken, estimates of future penetration rates will be a critical element in the debate over the proper "cost" per subscriber of the loop plant. Optimistic estimates of penetration can lead to underpricing, and either substantial under-recovery of capital investment, or a shift of the capital costs to other ratepayers. The latter outcome will be difficult to avoid, especially if fiber installation is lumped with other investments in loop plant. As analyzed here, an IBN clearly falls under the category of a "basic" service. As such, investments in fiber in the local loop are included for ratemaking purposes with investments in copper loop plant. Attempts to separate investment in an IBN so as to avoid these problems will likely founder on the inability to distinguish between fiber installed in anticipation of eventual video delivery, and fiber installed today to reduce the cost of copper in the loop plant through multiplexing.

A State Public Utility Commission faced with a request by the local exchange carrier for a certificate of "public interest convenience and necessity" to construct a fiber loop network has a difficult decision to make. The PUC's burden can be eased if there is some way to shift the risk of failure away from the POTS ratepayer.

The LEC can better its chances for PUC approval by engaging the local CATV franchise in a joint venture (Baer 1984). A long-term contract with a cable operator to provide video transport services over an IBN shifts the subscriber penetration risk from the regulated PUC to the unregulated cable franchise. However, an IBN threatens the cable operators's franchise monopoly, for it makes it possible for there to be many sources for video programming.

Finally, if the PUCs were to move from overall rate-of-return regulation to a price cap on basic voice service, then the risk of the investment in an IBN can be shifted to the shareholders of the LEC. Since revenue from POTS is capped, any losses which result from a failure to correctly gauge the market for an IBN cannot be passed on to the POTS ratepayer. By the same token, the LEC would then be in a position to reap fully the rewards of establishing a successful IBN.

In sum, the broadband ISDN threatens to abolish forever the distinction between point-to-point and mass media, and force a collision among two long separated traditions of public policy and regulation.

Notes

1. A close relative to the bus is the ring topology which connects all subscribers onto a single bus that circles back to its origin. The ring approach has the advantage of increasing network reliability; if a node on the bus fails or the line is cut, the bus can operate in a reverse direction and only those subscriber near the outage lose service. Fujitsu of Japan has proposed a ring architecture in the feeder loop (Fujimoto 1989). A Bellcore report concluded that the additional electronic complexity associated with a ring architecture leads to prohibitively high costs (Bellcore 1989).

2. Technically, the DLC system is also a hybrid system because it uses fiber in the feeder and copper in the distribution portions of the network. However, for labeling purposes only, a hybrid system in this analysis refers to a hybrid network where the change from one transmission medium to another occurs at the curb or pedestal rather than the RDU.

3. Raynet was the first vendor to announce a FTTC product in 1988. See F. Dawson, in *Lightwave*, August 1988, p. 1. Since then several vendors have announced new FTTC systems and field trials. In *Telephony*, see A. Alexander, April 16, 1990, pp. 160-164; C. Wilson, April 2, 1990, pp. 9-10; C. Wilson, April 23, 1990, pp. 14-15.

4. PIN stands for positive intrinsic negative, which describes the structure of the semiconductor material in the photodetector.

5. The alternative is to convert the optical bus signal to electrical form briefly at every pedestal in order to remove or insert channels from or onto the bus using simple TDM techniques. Compared to non-intrusive taps, this approach adds to the pedestal cost because it requires a second transmitter/receiver pair in each pedestal although, as a benefit, it virtually eliminates power budget constraints and could allow a much larger number of pedestals to be served per fiber bus.

6. The study does not examine an all-fiber bus architecture for narrowband services, primarily due to the difficulties in upgrading such an architecture to broadband (Bellcore 1989).

7. The power budget limits the number of optical power splitters that may be placed in series (hence the degree of possible sharing of transmission resources). Ideally, an optical splitter dividing a signal eight ways introduces a loss of 9 dB. Thus, two in series (at the RDU and the pedestal) would result in a loss of 18 dB. The excess loss of the splitters due to their imperfect nature is likely to add a few more decibels to the overall loss figure. In any case, for the great majority of loop lengths, this architecture is well within the 40 dB power budget likely to be available to transport narrowband services.

8. Costs considerations lead us to assume AM modulation for the video signals are opposed to FM or digital. While saving money on video distribution, this choice would preclude other digital broadband services such as downloading databases.

9. A more integrated architecture would require only one receiver in the pedestal for both narrowband and broadband services. However, a Bellcore study reports that it will be difficult to combine the two analog signals together because of differences in signal power levels and optical interference (Menendez 1990).

10. *Underground* cable is cable buried below ground in conduit; *buried* cable is cable buried below ground without conduit. Underground cable is typically buried deeper and installed in high traffic network segments since more capacity can be added easily by pulling more cable through the conduit.

11. A major instance where the conclusions drawn from the analysis of a new construction scenario may differ from those of existing neighborhoods is the case of the hybrid network alternatives which make use of the current copper plant. If the existing copper drop can be easily connected to a new fiber network, total investment costs are reduced by the amount of copper drop relative to the new construction alternative.

12. This figure is computed on the basis of average residential lot size from the *Statistical Abstract of the United States*, 109th Edition, U.S. Department of Commerce, Table 1242.

13. The reinforcement strategy could take a number of forms, the least likely of which would be to completely retrench along the existing lines. If conduit was initially installed, the fiber could be pulled through at a cost of about $2.50 to $5 per meter. Alternatively, the capacity of the existing fiber could be more fully employed by either placing higher-speed electronics on each end of the fiber or using WDM or coherent transmission techniques.

14. Program ratings reflect the percentage of television sets (out of the group of all television sets, whether they are turned on or not) tuned to a particular program at one time. The viewing share is the percentage of operating television sets tuned to a particular program. Thus, the viewing share is always larger than the ratings, unless all television sets are turned on, in which case they are equal.

15. See, for example, Baskerville (1989); Faulkner (1989); Lu (1988); Lu (1990); Shumate (1990); Wagner (1989, No. 22).

16. This assumption is consistent with recent observations in the market for N-ISDN circuitry. Single chip implementations of the N-ISDN basic rate interface between the subscriber and the network using CMOS technology are now available on the market (Sallaerts 1987).

17. While this approach is under trial by equipment vendors, one vendor has opted to supply power to the remote pedestals using network powering from a parallel copper network. This eliminates the need for field-mounted batteries in the event of a power outage, which can be an operations and maintenance problem. For example, in the aftermath of Hurricane Hugo, some areas were without power for three weeks and simply maintaining remote DLC batteries, which are much less dispersed than pedestal batteries would be, turned out to be a monumental task. See Andrew Alexander, "Fiber Finds a Home at the Curb." *Telephony*, April 16, 1990, pp. 160-164. Southwestern Bell has concluded that power to the ONI should be provided by the subscriber with battery backup at the ONI. In this system, the ONI would detect and alert network personnel whenever a low-power condition existed and telephone company personnel would have to be dispatched to replace the batteries (Coleman 1990).

18. Storage Technology Corp. markets a $500,000 (non-video) tape cartridge loader that can sort and load 6,000 stored cartridges onto eight tape units in 11 seconds. DEC has an optical disk jukebox that holds 64 twelve-inch disks at a cost of $205,000. See *Electronic Business*, September 1, 1988, p. 20. Also E. Smalley, "Avalanche of Storage Products Includes Disk Arrays, Jukebox," *Digital Review*, January 30, 1989.

19. The engineering cost models were run on the Decision Modeling System (DEMOS) software package developed at Carnegie Mellon University. DEMOS is a quantitative assessment tool, somewhat like a computer spreadsheet, that creates an interactive environment for structuring, analyzing, and communicating probabilistic models. DEMOS is available from the Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, Pennsylvania, 15213. In addition, any of the engineering cost models discussed in this analysis are available from the authors upon request.

20. At first glance it may seem that one can treat the total costs as fixed, and easily convert the cost per home passed figures to different penetration levels. However, variable costs, are a (non-linear) function of the service penetration rates. The value of the total investment cost is not fixed, but varies with the penetration rate of the video services.

21. A probabilistic analysis could go one step further and estimate the *probability* that future costs will reach some value by attaching probability distributions to the cost estimates of the electronics components. However, the lack of prior knowledge limits the utility of such an exercise in this application. Estimating the shape and parameters (e.g., the first and second order moments) of the probability distributions associated with the cost of each electronic component would likely prove to be an arbitrary affair given what little data exist today.

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