Residential Broadband Services by Telephone Companies?

Technology, Economics, and Public Policy

Leland L. Johnson, David P. Reed

RAND

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PREFACE

This study assesses telephone companies' prospects for providing integrated broadband networks for voice, data, and television services to homes. Today they are prohibited from competing with cable companies in offering television services. Whether this prohibition should be lifted is a controversial issue whose resolution could markedly affect the conditions under which telecommunications services are made available to the American public.

This RAND study is the first of several dealing with legal, economic, and engineering issues that arise in connection with the market structure of television supply. A preliminary version of the study was presented at the Seventeenth Annual Telecommunications Policy Research Conference, Airlie House, Virginia, October 1–3, 1989.

The research was supported by grants from The Markle Foundation and from Richard S. Leghorn. Government legislative and regulatory bodies, cable television and telephone companies, consumer groups, and the academic research community may find it of particular interest.

David Reed, a RAND consultant, is in the doctoral program of the Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, Pennsylvania. Leland Johnson is a member of RAND's senior staff.

SUMMARY

A major policy debate surrounds the question of whether telephone companies should be permitted to offer television programs within their service areas in competition with cable television systems. The debate is sparked by (a) the potential emergence of integrated broadband networks (IBNs) using high-capacity fiber optic links to combine voice, data, and video services as a substitute for separate narrowband copper telephone lines and broadband television cable, and (b) allegations that cable television systems exercise monopoly power and that competition from telephone companies would lower prices and stimulate development of new services.

Telephone companies are generally prohibited from providing television programming within their service areas. Among the legal restrictions on their market entry is the ban on crossownership between cable and telephone systems adopted in 1970 by the Federal Communications Commission (FCC). This ban arose out of fear that if telephone companies were allowed into the television market, they would restrict access to their poles and conduits needed by cable operators.

However, in 1988 the FCC tentatively concluded that a policy of open entry by telephone companies, subject to safeguards against anticompetitive conduct, would better serve the public interest. Moreover, Congressional legislation has recently been drafted to permit entry under specified conditions. These developments are but two outgrowths of the controversy in which industry groups, government administrative and legislative bodies, the courts, and consumer groups are now enmeshed.

In this study we examine how telephone and cable companies might respond during the 1990s if the crossownership ban and other legal restrictions on market entry were lifted. We describe alternative networks that these firms might favor in light of the constraints imposed by technology, economics, and government regulation. We draw from an intensive review of the technical literature in estimating network costs, where anticipated technological advances play a key role, and we show how the results of our analysis are affected by alternative assumptions where uncertainty is particularly great.

Our analysis suggests that lifting the restrictions on telephone company entry would lead neither to increased competition in the television market nor to emergence of new services. Telephone and television services would continue to be offered on separate networks. The

networks would be owned either separately by telephone and cable companies as they are today, or one entity would own both.

These conclusions emerge largely because of the weak market we anticipate for switched, "on-demand" video—a service that would permit users to be switched (in the same way that telephone calls are switched) on a one-to-one basis to selections from a multitude of program sources. Switched video contrasts with nonswitched or distributive video that cable companies offer today. The role of switched video is critical because it is the only new residential service, at least at the outset, that we can foresee telephone companies providing with fiber. In the absence of switched video, the telephone company would be in a situation similar to that of an outside cable operator, who would face difficulties in entering the market against an incumbent operator because of the natural monopoly characteristics of the cable television industry.

We conclude that the market for switched video services is severely limited because of its high cost combined with competition from services already available on cable and video cassette recorders. Presumably, services already available on cable would be offered by the telephone company as well, either through an IBN or through a separate cable television network. That adding switched video services would not cover the additional cost is suggested by the fact that our cost estimates for switched video exceed the total—some $300 annually—that subscribers on average spend today for *all* cable television services.

Our estimated costs of an IBN are higher than the combined cost of separate narrowband and broadband networks that would offer the same services. Economies clearly exist in combining narrowband services such as switched voice and data, and in combining broadband services such as basic cable service and pay movie channels. However, economies appear not to exist in combining switched narrowband and nonswitched broadband services. Thus, our analysis suggests that if telephone companies enter the video market during the 1990s, they will do so by building cable television networks separate from their telephone networks (with coordinated construction and maintenance), rather than by constructing IBNs.

The prospects for IBNs are further dimmed by the possible problems of maintaining the reliability of telephone service at today's high levels. Telephone companies have confined their most fragile electronics to centralized locations, while using a rather simple copper network to reach their customers. In contrast, IBNs require a large investment in sophisticated electronic equipment in remote locations close to customers' homes. Not only would decentralization add to maintenance costs but, with integration of facilities, the failure of this equipment could disrupt both telephone and television service.

Moreover, many of the technological advances that enhance fiber's attractiveness to telephone companies would also enhance its attractiveness to cable systems, which pass more than 80 percent of the nation's homes. Some cable operators are retrofitting fiber in their backbone trunk lines, thereby improving signal quality, expanding channel capacity, and cutting maintenance costs. This process of gradually introducing fiber favors the cable operator. The use of fiber in trunk lines *immediately* improves video service to *all* downstream subscribers, since they are already attached to the cable network by broadband coaxial lines. But installation by the telephone company of fiber in its feeder lines does not, by itself, provide *any* video service to telephone subscribers because they are connected to the network only with narrowband copper lines. Thus, cable operators can progressively retrofit portions of their plant, simultaneously improving service quality, while telephone companies face a potentially expensive cutover to bring video to telephone subscribers. Without a strong demand for switched video, telephone companies may never be able to cover the costs of offering nonswitched video in competition with cable systems.

Despite these handicaps, would telephone companies nevertheless be able to compete by using cross-subsidies from their monopoly telephone markets? We conclude not, because the amount of required subsidy would be large and easy for regulators to spot. The use of price cap regulation for telephone service may further reduce the threat of cross-subsidization. If cross-subsidies occur at all, they are more likely in new communities without existing telecommunications facilities, where even small subsidies might tip the balance in favor of the telephone company in a close race to enter the video market before a cable operator.

Despite the apparently bleak prospects for competition between telephone and cable television companies and for development of new services, we cannot recommend on the basis of this study alone whether restrictions on telephone company entry should be retained or abolished. Several factors must be weighed before a recommendation can be made.

On the side of removing the restrictions are the possibilities that (a) seeking to compete with cable, telephone companies may take approaches to broadband fiber R&D different from those of cable operators, possibly leading to unanticipated breakthroughs in broadband technology and perhaps spillovers that would reduce the cost of basic telephone service as well, and (b) cost savings might accrue from common ownership of separate telephone and cable television networks.

On the other side, common ownership could undesirably foreclose potential competition in other, nonvideo information markets, and problems posed by potential cross-subsidization of video services supplied by telephone companies must be further assessed.

Questions would also remain about appropriate public policy if a move from the status quo is warranted. Whether telephone companies should be permitted to program some or all channels, as cable operators are now allowed to do, or whether they should serve only as common carriers, raises issues of how program diversity and First Amendment protection would be affected. In this study we simply assume that the telephone companies would be given full leeway to pursue whatever activities are most lucrative to show that, even with total freedom in programming, telephone companies are unlikely to succeed in competing against existing cable operators. The effects on program diversity and First Amendment rights of alternative arrangements for program supply must await further study.

Finally, we emphasize that because we deal with new and advanced technologies that may (or may not) emerge during the 1990s, our cost estimates and conclusions are necessarily uncertain and controversial. The most important contribution of this report is not our specific estimates, but rather our analytic framework with which readers may assess the consequences of introducing their own assumptions and other inputs.

ACKNOWLEDGMENTS

We very much appreciate the detailed comments on a draft of this report provided by RAND colleague Joseph Benzoni and Professor John Panzar of Northwestern University. We are indebted to Professor Marvin Sirbu of Carnegie Mellon University for helpful discussions during the course of the project. We further benefited from the help of RAND colleagues Bridger Mitchell, who patiently answered our many questions throughout, and Jan Paul Acton, who offered suggestions for improving the quality of the final product.

The usual disclaimer that the findings are not necessarily shared by sponsors or reviewers, and that the authors bear full responsibility for errors of fact and interpretation, applies with particular force in this case, where the subject is so complex and controversial.

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I. INTRODUCTION

Much attention has been devoted to the potential emergence of integrated broadband networks (IBNs) that combine voice, data, and video services on one network. This interest has been triggered largely by the development of high-capacity fiber optic links as a lower-cost substitute for copper in telephone lines and television cable. Thus, optical transmission technology might enable the integration of narrowband services now offered by telephone companies with broadband services offered by cable television systems.

PROHIBITIONS ON ENTRY BY TELEPHONE COMPANIES

In a few instances, cable television companies have sought to offer voice and data service in competition with telephone companies, but these applications have been quite limited because of (a) the technical problems in using cable's tree and branch networks for switched, two-way, voice and data services, and (b) the difficulties of dealing with state regulatory commissions. At the same time, telephone companies have not been physically able to provide conventional full-motion video, in competition with cable television, because of the capacity limitations of copper wire pairs in the local loop required today to connect households to the telephone network. In addition, under the Federal Communications Commission's (FCC) crossownership rules, adopted in 1970, they are generally prohibited from building broadband plant (either integrated with or separate from their narrowband facilities) to offer their own video services within their operating territories.[1] These restrictions are also codified in the Cable Communications Policy Act of 1984.[2] Moreover, the provision of video would be construed as an "information" service that is prohibited under terms of the Modified Final Judgment in connection with the AT&T divestiture. Thus, Bell

[1]Section 63.54 of the Communications Act of 1934 as amended states that "no telephone common carrier subject in whole or in part to the Communications Act of 1934 shall engage in the provision of video programming to the viewing public in its telephone service area, either directly, or indirectly through an affiliate owned by, operated by, or under common control with the telephone common carrier." This prohibition can be waived in rural areas, with specified characteristics, where cable television service might otherwise not be available.

[2]P. L. 98–549, 47 U.S.C. 55 521. Pepper (1988) provides an excellent survey of the regulatory, legal, and economic issues surrounding the development of IBNs, with many citations to the literature.

operating companies would not be permitted to offer the service (in the absence of a court waiver) even if the crossownership and Cable Act restrictions were lifted.

These restrictions do not apply to a telephone company's building and leasing video facilities to independent, franchised video service suppliers. But few cable operators have exercised the option of leasing plant from telephone companies. Rather, they have overwhelmingly chosen to build their own plant, leasing only pole rights and conduit space from telephone companies.

The FCC's crossownership restrictions also do not apply if the telephone company offers video services as a common carrier—that is, if it provides channels under tariff on a nondiscriminatory basis to all potential users. But the Cable Act requires that even common carrier service would require that program suppliers have a franchise from the local government authority.

These prohibitions on the telephone company arose from fears that (a) they would restrict access to their poles and conduits to disadvantage cable competitors, (b) they might shift the costs of video service to their telephone customers, enabling them to cut prices for video service and to drive out or discourage entry by cable operators, and (c) government regulated carriers that are permitted to provide information such as video (i.e., to serve as publishers) may adversely affect the diversity of voices, raising concerns about First Amendment protections.

THE CURRENT CONTROVERSY

In 1988, the FCC tentatively concluded that the public interest would be better served by dropping the crossownership restrictions, on grounds that access to poles and conduits is a much less serious problem now than in earlier years, and that competition between telephone and cable television operators would tend to reduce prices and encourage new services. In the words of the Commission:

> On the one hand, where independent cable service is available (roughly 80 percent of the homes nationwide), entry by telephone companies would seem to bring all the benefits generally associated with competition, including greater choice for consumers, greater innovation, lower prices, and greater responsiveness to consumer demand. On the other hand, where independent cable service does not now exist, telephone company entry would bring new services to areas previously unserved.[3]

[3]FCC (1988), p. 5873.

The FCC's tentative conclusion was based in part on concerns that cable faces less-effective competition than was predicted in 1984 when the Cable Act was passed. Cable has thrived despite the growth of the VCR and the video cassette rental markets, the development of multipoint, multichannel microwave distribution of video signals, the use of satellite links for master antenna service, and continued growth in the number of broadcast stations. As evidence of the limited degree of competition, many point to (a) the high selling prices of existing cable systems (more than $2000 per subscriber) relative to construction costs (in the neighborhood of $600 per subscriber)[4] and (b) the substantial recent increases in basic subscriber rates accompanied by no perceptible decline in subscribership, after most government controls on rates were lifted as stipulated by the Cable Act.[5]

The circumstances surrounding the FCC's tentative conclusion have generated heated controversy. As one telephone industry spokesman puts it:

> The local exchange companies [must] be permitted to carry broadband—without distinction as to type of signal—within our local services areas . . . both our industry and our society will be severely short changed if we continue to arbitrarily separate these information channels.[6]

Six member companies of the Motion Picture Association of America similarly argue that "There is no more promising potential competitor to cable—in terms of capital and competitive zeal—than the nation's local exchange telephone companies, particularly the Bell Operating Companies."[7]

The cable industry holds quite different views:

> The adverse effects on existing competitors in the video marketplace—not only cable operators, but also broadcasters, program providers, video stores and others—are not weighed in the Commission's calculus. Nor are the costs that would be borne by captive telephone ratepayers to subsidize the telephone companies' predatory extension of their monopolies—including the quarter- to

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[4]See, for example, Shooshan & Jackson (1987a). For contrary views about the validity of measuring market power by dividing the market value of the firm by the replacement cost of its assets (the "Tobin q") see Grossman (1990) and MacAvoy (1990).

[5]According to one survey, basic service rates rose by about 29 percent between December 1986 and October 1988. General Accounting Office (1989), p. 1. For a response to the GAO study, see National Cable Television Association (undated).

[6]*Media Business,* October 23, 1989, p. 1.

[7]As reported in *Telecommunication Reports,* March 19, 1990, p. 49.

> half-trillion dollar tab necessary to finance the premature and otherwise unjustified construction of broadband facilities.[8]

In response to its tentative conclusion, the FCC has been deluged with thousands of pages of filings by dozens of interested parties. At this writing it has made no further decision about whether, and under what circumstances, telephone companies should be permitted to enter the television market.

However, the FCC has launched a companion inquiry in response to growing concern

> about whether cable has begun to abuse its power in the video services marketplace. There are increasing consumer complaints about high and rising basic cable rates, poor service quality, and the dropping or repositioning of broadcast signals.[9]

Whether other transmission options, including those provided by telephone companies, may affect local market competition is of central relevance to the FCC's new inquiry.

In parallel with the FCC's investigations, Congress has been active. Two bills have been introduced in the 101st Congress—S.1068 and H.R. 2437—that would permit telephone company entry into video delivery.

Three aspects of the debate are especially notable. First, much attention has focused on telephone company provision of switched, "on-demand" video. In the same way that a telephone caller can be switched to any one of multiple parties, a video user could be switched on demand to any one of a multitude of program sources. Use of a "video jukebox," as it is sometimes described, would permit subscribers to select from a huge video library of educational, cultural, and entertainment offerings. At least one study views the emergence of such switched services as "inevitable":

> Modern technology, combined with consumer needs, has made the ultimate adoption of switched, high bandwidth services to the home inevitable, unless some major catastrophe, such as nuclear war or melting of the polar icecaps, upsets the economy. This inevitability arises from two causes: (1) the availability of fiber optic communication systems, and (2) consumers' needs for communications.[10]

The role of switched video is of critical importance because, at the outset at least, it is the only new residential service that we foresee

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[8]*Reply Comments of Time Incorporated,* FCC CC Docket No. 87-266, January 27, 1989.

[9]FCC (1989), p. 4.

[10]Shooshan & Jackson (1987a)

telephone companies providing with fiber. Almost all imaginable information services to the home can be supplied by today's telephone and cable TV systems.[11] Telephone lines can be used for personal computer links, home shopping, financial transactions, and access to a multitude of information services. Cable television supplies dozens of channels and, with the increasing use of addressable set-top converters, it supplies pay-per-view programs as well. The basic conclusions of our study are driven by whether switched video is cost-effective in light of the multitude of existing services.

Second, the issue arises as to whether two video networks, or only one, would emerge. If economies of scale exist in provision of a service—a reduction in unit cost as the scale of output increases—we would expect television service to be offered as a "natural" monopoly. If economies of scope also exist—a reduction in the overall cost of offering services together rather than separately—we would expect voice, data, and video services to be offered together on a "single wire" by a monopoly carrier. In contrast, the possibility that socially beneficial competition could result—one that led the FCC to its conclusion in 1988 that telephone company entry would serve the public interest—has driven much of the debate. The telephone industry also has emphasized the competitive aspect. As the United States Telephone Association asserts, "Telco provided video is an alternative to current viewing choices. The issue here is not *one* wire, but one *more* wire."[12]

Unfortunately, the debate has been couched in very general terms. Little empirical evidence has been offered about the costs of alternative network configurations and combinations. In a few cases, estimates of costs per subscriber are displayed, but with no specification of household density, the percentage of households that sign up for the service, or basic technical characteristics.[13]

Third, issues arise of whether telephone companies should be restricted to common carrier video services, or whether they should be permitted to program some or all of their channels, as do cable operators today.[14] This issue raises First Amendment and other concerns that must await later analysis.

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[11]For a brief discussion of such services see Nynex (undated).

[12]United States Telephone Association (undated).

[13]See, for example, Comments of Corning Glass Works, FCC CC Docket No. 87–266, November 2, 1987.

[14]See, for example, the recommendations by the National Telecommunications and Information Administration (1988).

PURPOSE, METHODOLOGY, AND ORGANIZATION

Purpose

This study is concerned with the likely consequences, during the 1990s, of lifting barriers to telephone company entry into the video market.

- Would the telephone company construct an integrated network or would it construct a narrowband network for voice and data and a separate broadband network for video services, similar to the separate networks in place today?
- Would provision of on-demand video be financially attractive to telephone companies?
- Would telephone and cable companies compete in the video market as envisioned in the FCC's tentative conclusion?
- How would government regulation of telephone rates affect outcomes?
- What are the implications for public policy?

It addresses these questions under three basic assumptions.

- All legal barriers to telephone company provision of video programming and transport—federal, state, and local—are swept away. Telephone companies have full freedom to operate either as common carriers or as programmers, or in whatever combination would be most financially attractive for them.
- They have access to the supply of programming under the same terms as do cable operators.
- They are free of government regulation of rates for video programming services—as most cable operators are today—but remain subject to regulation of their narrowband services as telephone carriers are today.[15]

It is important to define our use of the terms "telephone company" and "cable television company." A telephone company provides switched voice and data (narrowband) services, and may provide video transmission on a lease back or common carrier basis as noted above. With removal of the current legal ban it may also provide video programming. Video services may include those available today through cable companies: *basic* channels for retransmission of signals from

[15]Under the Cable Act, cable operators were freed of rate regulation except in areas served by fewer than three over-the-air broadcasting stations. 50FR 18637 (May 2, 1985); 3FCC Rcd 2617 (1988).

broadcasting stations, carriage of cable television networks such as CNN, and local programming; *pay* channels that include movie packages; and *pay-per-view* offerings that permit the subscriber to pay separately for certain programs, usually "big ticket" movies, live sports, and musical events. The firm may also offer switched, on-demand video service as described above.

A "cable television company" may offer any of the video services described above but does not offer switched narrowband service. Or, to put it differently, if it chooses to offer switched narrowband service, it becomes a telephone company. Thus, the only distinction between these two types of firms in our analysis involves whether they do or do not offer switched narrowband service.

Methodology

Our basic approach involves (a) estimating costs of alternative network designs, in light of differences between new large communities where telecommunications networks are yet to be built, and existing communities where telephone and cable television systems are in place, (b) examining the likely behavior of telephone and cable television companies faced with choices among alternative technologies, taking into account the effects of government regulatory policy, competitive pressures, and changes in market conditions, and (c) drawing from the above to trace implications for public policy.

Obviously, analysis of new and advanced technologies that may (or may not) emerge during the 1990s is subject to great uncertainty. In response, we have emphasized four approaches to strengthening the credibility and usefulness of our study:

- Intensive review of the technical literature, cited throughout, to strengthen the basis for our network designs and cost estimates.
- Use of sensitivity analysis to test the effects of alternative assumptions and quantitative estimates.
- Explanations of our estimates in sufficient detail to enable readers to easily replicate the results.
- Presentation of preliminary analysis and findings at professional meetings to obtain comments from participants.[16]

[16]These presentations were made at the Seventeenth Annual Telecommunications Policy Conference, Airlie House, Virginia, October 3, 1989; the "New Video Marketplace" Conference sponsored by the Telecomm Publishing Group, Atlanta, Georgia, November 13, 1989; "The Future of Broadband Services to the Home" seminar, Annenburg School of Communications, University of Southern California, Los Angeles, February 5, 1990; and the ICC/SUPERCOMM '90 Convention, Atlanta, Georgia, April 17, 1990.

In light of the many uncertainties about network costs and market conditions, the most important contribution of this report is not our specific estimates, but rather our analytic framework into which readers may assess the consequences of introducing their own assumptions and other inputs.[17]

Organization

In Sec. II we introduce a base case that involves assessment of a particular IBN design—the active double star network—applied to a hypothetical new residential community without existing telephone or cable television service. Section III covers alternative network architectures in this hypothetical community. Section IV discusses the role of competition with cable operators and the potential effects of government rate regulation. Section V treats the complications of introducing fiber into communities where telephone and cable facilities are already in place. Implications for public policy are treated in Sec. VI, and overall conclusions are drawn in Sec. VII. More detailed treatment of the technical characteristics and cost estimates of networks is included in the appendixes.

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[17]This framework draws from an earlier study by Sirbu et al. (1989).

II. NEW RESIDENTIAL CONSTRUCTION: BASE CASE NETWORK

We start with a case that is most favorable to telephone company construction and ownership of facilities that include video service.

- All construction is in a new large residential community where no telecommunications plant exists and where installation costs are reduced by synchronizing plant construction with that of streets, sidewalks, and other infrastructure.
- The telephone company is "first mover" in providing video service, so it faces no competition from an incumbent cable operator.
- The plant is built instantly, with no costs incurred for plant under construction.
- Market response by households is also instantaneous, with purchase of specified services immediately rising to the levels postulated in our various cases.

The key questions to be addressed in this section are:

- Does the telephone company construct an integrated broadband network, or does it construct a narrowband network for voice and data and a separate cable TV network for video services, similar to those in place today?
- Is provision of switched video financially attractive to the company?

We consider the active double star network as our base case because:

- The active double star resembles the digital loop carrier used in today's telephone networks for narrowband services, making evolution to this architecture simpler than for alternatives.
- Much of the ongoing effort on developing prototype IBN components is based on this architecture.
- The active double star is generally cited by telephone company analysts as the most likely approach for IBNs.[1]

[1]See, for example, Shumate (1989).

THE NETWORK MODEL

The active double star architecture involves connecting the central office by feeder fiber to remote distribution units (RDUs), which are connected to individual homes with fiber distribution lines, illustrated in Fig. 1 and discussed in greater detail in Appendix A. By equipping the RDU with a switching capability, individually selected channels can be provided to homes from the signals multiplexed on the feeder cable from the central office. Multiplexing signals between the RDU and the central office reduces costs below those of a single switched star alternative, discussed in Sec. III, where individual channels would be switched at the central office.

We assume that all construction is below ground within a service area that encompasses a square of 1024 households, 32 homes on a side, laid out in a grid of square blocks with a mean housing density of 88 homes per street mile.[2] The RDU is located in the center of the

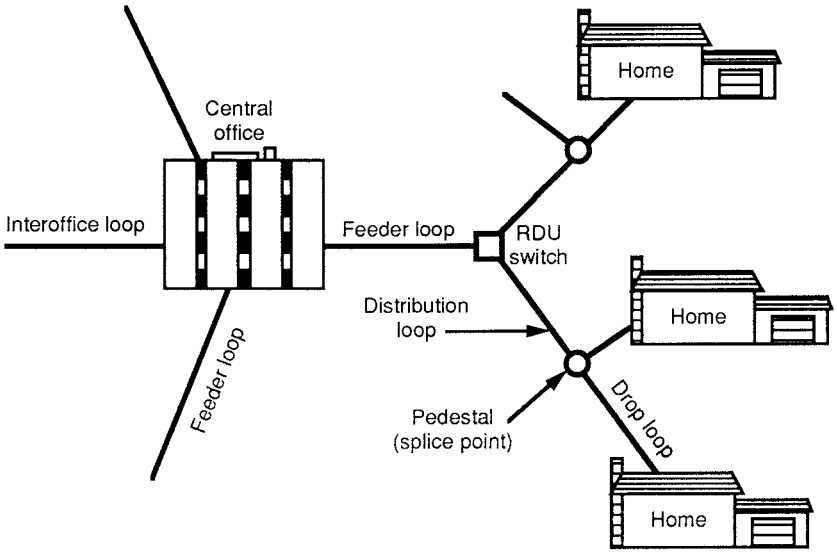

Fig. 1—Active double star network

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

service area, a distance of 3072 meters from the central office.[3] In our model, 24 RDUs plus the central office itself (which serves as one RDU) cover a total of 25,600 households.

We use costs substantially below current levels for optical fiber and associated electronics equipment to account for technological advance during the 1990s. For example, we assume three levels of optical fiber cost—5, 10, and 20 cents per meter. Today, fiber costs in the neighborhood of 20 cents per meter.

Because cable installation is expensive, we assume a one-time installation of feeder, distribution, and drop fibers for voice and video to all homes.[4] Once the field engineering, installation equipment, and labor have been diverted from a neighborhood, it would be prohibitively costly to return to the area for further installation, especially for underground construction. However, we assume that electronics equipment is installed only as demand warrants.

Our model includes 622 megabits per second (Mb/s) capacity in the distribution loop between the RDU and the home.[5] This bandwidth is enough for four uncompressed conventional video signals or for some number (equal to or less than four high-definition television (HDTV) channels) in addition to a narrowband signal.

We assume that all households in the service area subscribe to telephone service and that varying percentages also subscribe to video services. The video package gives each subscriber a single switched video channel with which he may select either from among 64 "distributed" (nonswitched) video channels, comparable to today's basic, pay, and pay-per-view cable television services, or from an on-demand video offering. We assume that 20 percent of the video subscribers request access to a second switched video channel, with the usage on the second channel equal to one-half the usage on the primary channel. To allow for future growth, the video switch at the RDU provides up to four switched video channels per subscriber and the electronics

[3]The distance of 3072 meters is typical in the telephone industry. See Singh (1987), pp. 32–37.

[4]The amount of feeder fiber deployed initially would depend upon the forecasted rate at which subscribers sign up for broadband 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. See Reed and Sirbu (1989b).

[5]We assume use of the SONET (synchronous optical network) standard, which describes a family of synchronous transport signals (STS), designated as STS-M for electrical signals supporting M signals of multiples of 51.84 Mb/s. The CCITT is considering standard broadband subscriber interfaces at the STS-1 and STS-12 rates, corresponding to 51.84 Mb/s and 622.08 Mb/s, respectively. For an expanded discussion see Appendix A.

components that would be needed to transmit the signals (although the equipment at the customer's home contains only the capacity currently required).

The demand for broadband services determines the number of feeder fibers needed in the feeder loop, in addition to the amount of associated electronics required at each end of the fiber in the central office and RDU. At one extreme, suppose all households watch only the distributed video channels to the exclusion of switched video channels. In this case, if we assume a feeder capacity of 2.4 Gb/s (the STS-48 rate) capable of carrying 16 video signals (each at the STS-3 rate), four feeders could provide up to 64 distributed video channels. At the other extreme, if all households simultaneously watched a separate switched program, each would require a dedicated channel in the feeder loop. If the RDU serves 1024 subscribers, an additional 64 feeder fibers (1024 $\div$ 16) would be required for the switched video in addition to the four noted above for the 64 distributive video channels.

The sensitivity of network design to demand assumptions depends in large part upon the degree of sharing in the transmission medium, which in the active double star architecture occurs in the feeder loop.[6] Designing the network requires estimates of traffic patterns for broadband services, especially those requiring a dedicated video channel such as on-demand switched video.

We estimate the number of channels required for on-demand video with traditional traffic engineering techniques.[7] A key parameter is the percentage of subscribers requesting a channel during the peak busy viewing hour. It is given by the product of the average hourly video traffic per subscriber per week (A) and the percentage of weekly traffic that occurs during the peak busy hour (p). For example, if the average subscriber views one 90 minute on-demand video per week ($A = 1.5$) and 10 percent of the traffic occurs during the peak busy hour ($p = 0.1$), the percentage of subscribers during the peak hour is 15 (given by $100Ap$).

This figure of 15 percent could be interpreted as the "viewing share" of on-demand video, representing the percentage of all televisions in video subscriber homes tuned to on-demand service during the peak hour. To reflect uncertainty about the number of subscribers who request a switched channel, we consider values for A ranging between 45 minutes and 6 hours per subscriber per week.

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[6]For a discussion of the relationship between the demand for broadband services and an alternative network design that upgrades cable television networks with fiber backbones, see Reed and Sirbu (1989a).

[7]The calculations assume a full availability loss system modeled by the Erlang B formula with a grade of service equal to 1 percent. See Schwartz (1987).

One would not expect the relationship between the percentage of peak busy hour subscribers and A to be linear over the entire range of A. An increase in A reflects multiple viewings of videos spread over the entire week. Therefore, the percentage of weekly video traffic during the busy hour, p, would decrease. Over the range of A covering 0.75, 1.5, 3, and 6 hours per week, we assume in our base case that the percentage of peak busy hour subscribers is equal to 7.5, 15, 24, and 30, respectively.[8] The sensitivity (which is not great) of our results to this assumption is shown in Appendix B.

NETWORK INVESTMENT COSTS

Network investment costs are shown in Table 1. For example, with a fiber cost of 10 cents per meter and an IBN video penetration level of 60 percent, we estimate that the IBN investment cost would range from $1663 *per home passed* for low levels of on-demand viewing to $1754 for high levels. The composition of the investment costs for the case of fiber costing 10 cents per meter is contained in Table A.2 in Appendix A.

The estimates in Table 1 highlight three important considerations. First, overall costs are affected by the capacity required for alternative levels of demand for switched video. This result should not be surprising, but it is useful to keep in mind when confronted with frequently voiced assertions that fiber has virtually "unlimited" capacity. In fact, it does have limited capacity, in any meaningful economic sense, and the cost of using fiber and its electronics components depends on traffic demands. This situation suggests that peak-load pricing of on-

Table 1

INVESTMENT COST OF INTEGRATED NETWORK PER HOME PASSED, 60 PERCENT VIDEO PENETRATION
(In dollars)

Cost of Fiber ($/Meter)	Hours of On-Demand Video per Week per Subscriber			
	0.75	1.5	3	6
0.05	1610	1630	1657	1693
0.10	1663	1683	1710	1754
0.20	1769	1789	1816	1875

[8]Thus, we assume a p of 0.10, 0.10, 0.08, and 0.05, respectively.

demand channels may play an important role in promoting economic efficiency in use of the network.

Second, the figures are only moderately sensitive to the cost of fiber. A reduction from 20 cents to 5 cents per meter would reduce investment cost by 11 percent or less for all levels of viewing at the 60 percent level of video penetration. Indeed, even if fiber cost were to fall to zero, total investment would fall only by about 6 percent below the level given by a fiber cost of 10 cents per meter. Of greater importance is the cost of ducts, sheathing, electronics, and installation. *Our subsequent estimates will use the figure of 10 cents per meter for the cost of fiber.*

Third, one of the greatest uncertainties in the analysis is whether environmental control (e.g., humidity and temperature) will be needed for the optical/electrical interfaces and other electronics (listed in Table A.6) located on or near the customer's home. The larger the bandwidth requirements, the greater the chances that environmental protection will be needed. Environmental protection is easy if the equipment is located *inside* the home. But maintenance of the equipment, requiring housecalls, would be a nightmare, especially since failures would disrupt *both* telephone and television service. Therefore the equipment must be located outside. We assume that no protection will be needed, so do not include it in the cost estimates. If protection is required, however, capital costs could rise by hundreds of dollars per video subscriber.[9]

THE VIDEO JUKEBOX AND HEADEND

Table 1 shows only the network investment costs of fiber, switching, and associated electronic equipment. Provisions for feeding video services into the network, passing 25,600 homes (encompassing 25 service areas each of 1024 homes as described above), must also be considered.

The headend facilities for feeding the distributed video signals into the network are similar to those for a conventional cable television system. Cost estimation is straightforward, as treated in Appendix C. The estimated investment cost for 60 percent video penetration is $243,100 or a relatively small $10 per home passed.

Estimating the cost of a video jukebox is more challenging. Present-day jukebox systems can select and load tape cartridges or optical disks from a library sometimes involving thousands of items.

[9]This situation illustrates again why talk of fiber's "unlimited capacity" is misleading. As capacity rises, the need for environmental protection of electronics also rises, perhaps to prohibitively costly levels for residential use of broadband fiber services.

However, no off-the-shelf technology exists for playing back videotapes upon request or, for that matter, allowing several subscribers simultaneous access to a single copy of a video program. The problem is that with a headend serving 10,000 to 20,000 video subscribers (depending on the level of video penetration in our model), several thousand channels might be requested during the busy hour.[10]

As discussed in more detail in Appendix C, we assume the use of videotapes and VCRs in the video jukebox. To be sure, technologies are emerging with compact digital storage that could eventually be more attractive than the use of tapes. For example, digital video interactive technology is now being introduced that stores the program in a highly compressed digital format, to be later decompressed and displayed in real time. Optical disks capable of storing large amounts of information (in the gigabyte range) are now available. However, it is doubtful that digital technologies will become fully suitable for use in these applications during the 1990s. We will assume that with advanced versions of today's technology, a jukebox selector and loader capable of handling thousands of requests will cost $800,000, with a video player cost of $200 per channel.

We also assume that the video library has 5000 titles—equivalent to an inventory of a large video cassette rental outlet in today's market. Because of the need to hold multiple copies of frequently requested movies (today's video outlets may hold as many as 100 copies of a popular video), we assume that 1 percent of the titles have 100 copies and that 75 percent of the titles have at least one backup copy. We estimate that, under these conditions, 14,110 to 25,550 programs (at a cost of $5 per copy) are held in the video library, depending on the level of video subscriber penetration and peak demand patterns.[11] Moreover, 3000 VCRs would be required for an average of 1.5 hours per week per subscriber, at a 60 percent video penetration level.[12] The

[10]If each channel requires a separate VCR player, problems arise as to how one might economically house and operate several thousand VCRs with an automated jukebox.

[11]The estimate of $5 includes the cost of tapes and reproduction of programming, but not royalties or other payments to program suppliers, which are treated separately below. The switched system can draw from sources in addition to those in the tape library. For example, some programs on local low-power television stations are not always carried on cable because of capacity constraints. Switched video, on either a common carrier or noncommon carrier basis, would greatly expand the possibilities for access to these programs. See "Low-Power TV: Coming of Age in Uncertain Times," *Broadcasting,* April 9, 1990, p. 60.

[12]This seemingly very high figure for VCRs reflects the peaking in demand for service across thousands of subscribers. Costs of the jukebox and tape inventory could be greatly reduced if delays of minutes or hours were permitted in filling customer requests for service. But the longer the delays, the closer would the service resemble today's offerings on cable television. Peak-load pricing of service might also reduce these costs.

investment cost for the jukebox and headend is shown in Table 2, with disaggregations treated in Appendix C.

Table 2 shows that headend and jukebox costs are a rather small percentage of total network cost per home passed. The highest cost in Table 2 for 60 percent penetration ($106) is about 6 percent of the corresponding figure (with fiber costing 10 cents per meter) in Table 1. Thus, even if our assumptions are wide of the mark, they may not have great consequence in the overall analysis.

Table 3 shows total investment cost, consisting of the figures from Table 2 added to the appropriate network investment costs. Because cost is sensitive to level of video penetration, we will continue to report results for all three levels of video subscribership.

Table 2

INVESTMENT COST OF HEADEND AND VIDEO JUKEBOX PER HOME PASSED
(In dollars)

% On-Demand Video Penetration	Hours of On-Demand Video per Week per Subscriber			
	0.75	1.5	3	6
40	57	67	79	87
60	62	77	95	106
80	67	87	110	126

Table 3

TOTAL INVESTMENT COST OF INTEGRATED BROADBAND NETWORK PER HOME PASSED, FIBER AT $0.10 PER METER
(In dollars)

% On-Demand Video Penetration	Hours of On-Demand Video per Week per Subscriber			
	0.75	1.5	3	6
40	1658	1636	1662	1699
60	1725	1760	1805	1860
80	1784	1831	1994	2075

INTEGRATED BROADBAND COMPARED WITH SEPARATE NETWORKS

A key question is whether the telephone company would find this integrated network more attractive than separate ones, each supplying a portion of the services. A conventional telephone narrowband network would supply the same voice and data services, while a conventional cable TV system would supply the same distributive video (but *not* switched video) services, as postulated above.

Annualized Investment Costs

To compare the costs of an IBN with those of separate networks, we convert investment costs to annual levelized estimates. These estimates must take into account the company's (real) cost of capital and the lifetimes of the facilities. We will take a figure of 13 percent for the narrowband network and 17 percent for the broadband network (pretax but net of inflation) to reflect overall differences in risk.[13] The company knows that all households will subscribe to telephone service and that, for residential service at least, the company will continue to have a monopoly.[14] In contrast, video service faces greater uncertainty involving, for example, the level of penetration for basic and pay services and the market for new services, especially switched video—of central interest in this study. Continued uncertainty about competition from alternative video systems, such as direct broadcast satellites and multichannel multipoint distribution systems, will add to investor risk.[15]

Another consideration is the economic lifetimes of network components. The physical portions of the plant will have longer useful lifetimes than the electronics, which will be especially susceptible to the effects of technological advance. We will assume a 10-year life for the electronics portion, and a 20-year life for the remainder (including the fiber strands).[16]

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[13]The basis for these estimates of the cost of capital is explained in Appendix I.

[14]Telephone companies do face some competition in provision of services to large business users. But their monopoly over residential and small business users seems secure during the foreseeable future. Perhaps during the next century the use of cellular telephones and other wireless technologies will provide a competitive alternative to wire into the home.

[15]As one example, the plans announced in early 1990 for an advanced direct broadcast satellite system "Sky Cable" had a markedly (although perhaps temporary) adverse effect on the price of cable company stocks. *Multichannel News,* March 5, 1990.

[16]The 20-year assumption is consistent with the evidence gathered by Mitchell (1989), p. 19, based on telephone company experience in California. The 13 percent cost of capital with 10- and 20-year time periods converts respectively to annuity factors of 0.18429

A Copper/Fiber Narrowband Network

We consider two cases: The first includes off-the-shelf fiber and copper components as the basis for estimating "current" network cost. The second considers cost reductions likely to be afforded by technological advance during the 1990s, as a basis for estimating future costs. In both cases, subscriber density is the same as above, with 100 percent telephone penetration. In line with current design practice, we assume a digital loop carrier narrowband network, which requires fiber in the feeder portion and copper in the distribution loop. Enough copper is initially installed to provide two lines per subscriber, with 20 percent of the customers requesting the second line.[17] We use a 13 percent discount rate, a 20-year life for the nonelectronic components, and a 10-year life for the electronic components, as discussed above.

The results are shown in Table 4, with Appendix E providing the detailed cost breakdown. Of central interest is our annualized investment current cost estimate of $136 per subscriber and a future cost estimate of $93, where the future cost of fiber is assumed to be $0.10 per meter. These numbers are significant in showing that, for residential areas similar to those in our analysis, the use of fiber even in a

Table 4

INVESTMENT COST OF COPPER/FIBER NARROWBAND HYBRID PER HOME PASSED
(In dollars)

	Current	Future
Investment		
Electronic	519	287
Nonelectronic	284	281
Total	803	568
Annualized cost		
Electronic	96[a]	53
Nonelectronic	40	40
Total	136	93

[a]The annualized cost for electronics of $96 is computed by multiplying the investment of $519 by the annuity factor 0.18429. Other annualized costs here and in later tables are computed in similar fashion by using the appropriate annuity factors noted above.

and 0.14235. The 17 percent cost of capital with 10- and 20-year time periods converts respectively to annuity factors of 0.21466 and 0.17769.

[17]The cost of the second line, installed with the first, is much less than the cost of installing a second line later (especially for the underground construction postulated here), even if only 20 percent of the second lines are used.

nonintegrated network, will reduce the costs of *local* telephone service, as lower-cost fiber components—confined mostly to electronic portions—are introduced into feeder lines.

A Cable Television Network

Similarly, a separate cable television network can carry all the distributive video (but not the switched video) offered by the integrated network. In Appendix G, we consider two cases: A conventional coaxial cable system and a coaxial/fiber hybrid that takes advantage of the technological advances assumed for the integrated network. We assume a 10- and 20-year lifetime, respectively, for electronic and nonelectronic components, and a 17 percent discount rate for video service as discussed above. The levelized annual costs are shown in Table 5. A notable characteristic is that the cable operator enjoys little investment cost savings by installing fiber. The primary advantage of using fiber lies in reducing the number of amplifiers. This reduction improves the quality of reception, permits an expansion of capacity, and reduces maintenance expenses as elaborated on below.

The Incremental Cost of Switched Video

Table 6 shows the combined costs of the (future cost) narrowband hybrid and the coaxial/fiber hybrid, taken from Tables 4 and 5. The difference in service between the two separate networks and the IBN is the *switched* video offered by the IBN. The additional annualized cost of constructing the IBN instead of two separate networks can, therefore, be considered as the incremental cost of offering switched video.

Annualizing the cost of an IBN raises the question of the appropriate cost of capital for the IBN, given that it consists of services (narrowband and video) with different degrees of risk. The company will have an overall *single* cost of capital reflecting the investor's reaction

Table 5

ANNUALIZED INVESTMENT COST OF CABLE TV NETWORK PER HOME PASSED
(In dollars)

% Subscriber Penetration	Coaxial	Coaxial-Fiber Hybrid
40	66	64
60	76	71
80	82	79

Table 6

COMBINED ANNUALIZED INVESTMENT COST OF NARROWBAND AND CABLE TV HYBRID NETWORKS PER HOME PASSED
(In dollars)

% Video Penetration	Annualized
40	157
60	164
80	172

to the levels and mixture of risk. Presumably this cost will reflect a weighted average of lower-risk narrowband and higher-risk video services. Because we are concerned with the *incremental* cost of switched video (including its cost of capital) we proceed as follows. As illustrated in Table 7, we subtract the costs of narrowband service of a copper/fiber hybrid from the total cost of the IBN. We assume that investors regard as a low-risk investment (13 percent as used above) a *least-cost* narrowband system, which is our copper/fiber hybrid. All additional costs of the IBN ($1024 and $168 in Table 7) are attributable to video services that incur a higher cost of capital (17 percent). After subtracting the cost of the nonswitched video network, we have the incremental cost of switched video, which we convert to a cost per video subscriber. This cost is then annualized to obtain the figure totaling $297 ($307 – $10 in Table 7)—an amount that corresponds to the figure in the appropriate cell in Table 8. In these calculations, we use 10- and 20-year lives, respectively, for the electronics and nonelectronics portions, as before.

Operating and Maintenance Expenses

In addition to the above comparisons of investment costs, we must consider annual operating and maintenance (O&M) costs, which are no less important than investment costs in assessing alternatives. Some analysts conclude that the maintenance cost of fiber is lower than for copper.[18] Conceivably, the maintenance costs of the integrated network could be sufficiently lower than those of the separate telephone and cable networks that the *overall* annual cost of the integrated

[18]For example, Ensdorf et al. (1988) conclude that fiber could reduce local loop maintenance costs by 25 to 50 percent.

Table 7

ANNUALIZED INCREMENTAL INVESTMENT COST FOR SWITCHED VIDEO SERVICE, 1.5 HOURS AVERAGE ON-DEMAND VIEWING PER WEEK, 60 PERCENT VIDEO PENETRATION
(In dollars)

	Electronics	Nonelectronics
IBN investment[a]	1311	449
Less narrowband investment[b]	287	281
Video IBN investment	1024	168
Less nonswitched video investment[c]	167	201
Switched video investment per home passed	857	−33
Switched video investment per video subscriber	1428	−55
Switched video annualized investment per video subscriber	307	−10

[a]See Table A.2.
[b]See Table 4.
[c]See Table G.2.

Table 8

ANNUALIZED INCREMENTAL INVESTMENT COST OF ON-DEMAND VIDEO SERVICE PER SUBSCRIBER
(In dollars)

% On-Demand Video Penetration	Hours of On-Demand Video per Week per Subscriber			
	0.75	1.5	3	6
40	410	426	440	462
60	284	297	313	331
80	219	232	247	264

network would fall below the combined overall costs of the separate networks with their copper components. In this case, the telephone company would prefer the integrated network even in the absence of a market for switched video.

Unfortunately, we have no satisfactory estimates of O&M expenditures for IBNs. Only after more field experience with fiber performance has accumulated will it be possible to predict whether and how much O&M expenditures will fall.

One instance where fiber networks clearly should reduce maintenance involves the moves and changes requested by customers.[19] Fiber should reduce these requirements because the additional bandwidth of fiber provides more flexibility in satisfying the customer's needs (through software changes) without having to physically alter the network.

But other requirements will tend to increase costs. First, and most important, the IBN requires a large investment in sophisticated electronic equipment in remote locations, including that at the customer's home listed in Appendix A. As noted above, with integration of facilities, the failure of this equipment would disrupt both telephone and television service. The problem is exacerbated by the fact that optical/electrical interfaces and other electronics would be required even for customers who subscribe *only* to telephone service. Telephone companies have provided highly reliable service because they have confined their most fragile electronics to centralized locations, while using a rather simple copper network to reach the customer.[20] For these reasons, additional maintenance may be required within an IBN to maintain telephone service at the level of reliability customers enjoy today.

Second, because fiber does not conduct electricity, telephone service would be disrupted during outages of power supplied by electric utilities. Backup batteries would be required at or near the customer's home, imposing additional maintenance costs to be paid either by the telephone company directly or by the customer. (The need for such emergency backup will be particularly annoying to subscribers who want only telephone service and who benefit not at all from the substitution of fiber for copper.)[21]

Third, much of whatever savings in maintenance are possible with fiber is already incorporated in our illustrative separate copper/fiber hybrid networks. For example, a key advantage of using fiber in cable TV systems lies in reducing the number of amplifiers in cascade. When one fails, all the downstream amplifiers also go out, with service

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[19]Ensdorf et al. (1988) conclude that up to 40 percent of such customer requests require outside plant modification or other activity, accounting for one-fourth of total maintenance time.

[20]To be sure, the substitution of fiber for copper in narrowband and broadband networks also requires the decentralization of electronics beyond the central office and headend. But the degree of decentralization is much less than that required for IBNs, which need sophisticated electronics at or near customers' homes.

[21]In our network model described in Appendix A, equipment at a customer's home is powered by a connection to the customer's regular power supply. Rechargeable backup batteries are installed at the splice points shown in Fig. 1, with emergency power carried by copper line to the customer. Batteries are located at the more accessible splice points rather than at the customer's home to reduce battery maintenance costs.

disrupted to all downstream customers. Fewer amplifiers improve reliability. Moreover, because each amplifier adds noise to the signal, a reduction in their number improves reception quality as well.[22]

Fourth, accidental digups of underground fiber (or breakage in aerial plant) is more costly to repair than is the case with copper because of the complexities associated with fiber splicing.[23]

In light of these considerations, no reason exists, on balance, to conclude that O&M expenses for IBNs—as a percentage of investment—are any lower than those for separate hybrid narrowband and broadband networks. Thus, we are probably safe in concentrating on relative investment costs.

THE OVERALL COST OF ON-DEMAND VIDEO SERVICE

Despite the problem of estimating O&M expenses for IBNs, we must consider these costs for switched video service to assess its economic viability. (Again, we focus on switched video service because it is the only notable *new* service that we can foresee, at least at the outset, by an integrated switched broadband network.) These costs, in addition to those displayed in Table 8, include not only incremental network maintenance expenses but also advertising and selling expenses, billing, customer relations, and maintenance of the video jukebox with its thousands of VCRs and videotapes estimated in Appendix C. (However, they exclude payments to program suppliers, which are treated separately below.)

We will examine the range of possible O&M expenses by drawing evidence from both the cable and telephone industry. First, Baldwin and McVoy (1988, p. 417) estimate that a typical urban cable system has O&M expenses (less programming costs) of about $124 annually per subscriber. Network maintenance constitutes $28 of that amount. With the installation of fiber, illustrated in our hybrid broadband cable system, network maintenance costs may fall for the reasons previously discussed. Let us assume that the use of fiber reduces network maintenance by 50 percent below the $28 figure. In this case, per subscriber O&M would fall to $110 or to about *18 percent* of the $614 cost per subscriber for the hybrid cable system shown in Table G.2.

As another source, we have learned in interviews that telephone network maintenance per line today costs from perhaps $60 to $80

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[22]Some cable systems have 30 to 40 amplifiers in cascade. Fiber backbones would reduce this number to two to five amplifiers. See Chiddix and Pangrac (1988).

[23]This splicing problem also exists for hybrid narrowband and broadband networks, but it is more severe for IBNs simply because they use more fiber.

annually. Network maintenance expenses are about 40 percent of total O&M.[24] If we take a $70 figure (implying a total O&M cost of $175) and reduce it by 50 percent to reflect network maintenance savings from fiber, O&M expense would run to $140 ($175 – $35) for our narrowband hybrid—*25 percent* of the $568 investment cost estimated in Table E.1.

In light of the above, we will take for illustrative purposes an incremental O&M expense for on-demand service equal to *15 percent* of the incremental investment of on-demand service.[25] On this basis, the total annual investment and O&M expenses are shown in Table 9.[26]

Whether on-demand service is financially attractive in light of the figures in Table 9 depends on revenues collected by the company and payments to program suppliers. To illustrate, suppose that viewers watch an average of two 1.5-hour programs per week for which they pay $6 each. Suppose further that the company splits the revenues 50:50 with the program supplier (a split typical for pay television programs).[27] The net of $312 per year would fall short of covering total costs even at an 80 percent penetration level.

Table 9

INCREMENTAL ANNUAL TOTAL COST OF ON-DEMAND VIDEO SERVICE PER SUBSCRIBER
(In dollars)

% On-Demand Video Penetration	Hours of On-Demand Video per Week per Subscriber			
	0.75	1.5	3	6
40	694	722	746	784
60	481	503	530	562
80	372	393	419	448

[24]FCC (1987), p. 24.

[25]The 15 percent estimate is lower than those in the outside sources to reflect the possibility that the *incremental* O&M expense for on-demand service falls below the average O&M expenses for the overall network.

[26]To obtain the estimates in Table 9 we multiply the investment per subscriber for switched video (e.g., $1373 in Table 7) by 15 percent and add the figures to those in Table 8 (e.g., $297) to obtain the estimates in Table 9 (e.g., $503).

[27]Some may argue that the company could reduce its programming costs by vertically integrating with program suppliers. In any event, the costs of producing programs would have to be covered.

The market for on-demand service is limited, in part, because it would be offered on top of the great diversity of basic and pay services already available on cable (and included in the costs of our IBNs described in Appendix A and the cable networks described in Appendix G). Presumably, these would be offered by the telephone company as well, either through an IBN or by construction of a separate broadband network. Especially, we assume that all subscribers to a separate cable system would have addressable converters that permit them to view programs on a "near" demand or pay-per-view basis. For example, they could request and pay separately for live sports and entertainment programs and could enjoy much of what otherwise could be offered by on-demand video. The principal difference is that near-demand video available (even today) with addressable converters requires that the viewer watch the program at a set time, but with the possibility of repeats, while on-demand video would permit the viewer to dial up on impulse a program from a wide inventory. The key question is, how much would viewers be willing to pay for this additional capability? The possibility that these payments would not cover costs is suggested, in part, by the fact that the costs displayed in Table 9 equal or exceed the total amount—about $300—that subscribers today pay for *all* cable television services.

The situation is further complicated by the substitution possibilities between on-demand service and other video services on the IBN. The telephone company must take into account how the offering on on-demand service affects, and is affected by, the revenues and costs of other services. For example, a household might not subscribe to a conventional pay TV channel in favor of on-demand service, resulting in a revenue loss for pay TV that must be considered in calculating the incremental revenues of on-demand service. Only if incremental revenues of on-demand service exceed its incremental costs would the firm find on-demand service profitable.

Moreover, one must remember that the potential difficulties noted above with respect to IBNs would be attributable to on-demand service to the extent that they would be avoided with the use of separate hybrid narrowband and broadband networks. These problems include the disruption of both telephone and television service when integrated electronics equipment fails, more dispersed optical/electrical interfaces, and the need for a new source of emergency power even by those who want only telephone service. Most important, if integrated broadband service requires environmental control for broadband electronics at or near the customer's home, the figures in Table 9 could rise by hundreds of dollars.

The core problem is that video switching, multiplexing, and equipment at the customer's home are expensive in the face of a possibly small market for switched services. The movement by cable operators to pay-per-view, along with continued growth of video cassette rentals and sales, will strengthen the alternatives to on-demand video.[28]

Finally, we must emphasize again that our estimates are uncertain. For this reason we have considered ranges of estimates for fiber costs, video penetration, and video receiving levels. An additional key uncertainty relates to the cost of powering an all-fiber network. As discussed in Appendix H, this is a far more important aspect than appears at first, because these costs could be very high. Our estimates in Table 9 include an investment cost (including emergency power) of more than $300 per home passed. Though high, this figure is lower than that estimated elsewhere. However, continued technological advances and new network architectures might reduce costs below our estimates. To test the sensitivity of our results to alternative power costs, we show in Table 10 the results for power cost reductions of 33 and 66 percent below our assumed levels. Even at the 80 percent level of penetration, most of the cases show that the incremental cost of switched video remains above today's average annual per subscriber revenues (of about $300) from all cable television services.[29]

Table 10

INCREMENTAL ANNUAL TOTAL COST OF ON-DEMAND VIDEO SERVICE PER SUBSCRIBER, 80 PERCENT VIDEO PENETRATION
(In dollars)

	Hours of On-Demand Video per Week per Subscriber			
Power Cost	0.75	1.5	3	6
Base case	372	393	419	448
33 percent reduction	314	336	362	390
66 percent reduction	257	278	304	333

[28]One source projects that the number of subscribers to pay-per-view offered on cable systems will grow from 8 million in 1989 to 24 million in 1992 or to more than one-half the households that currently subscribe to cable (Paul Kagan Associates, as reported in *New York Times,* February 12, 1990). Moreover, domestic and foreign video rentals and sales constitute 46 percent of the revenues of the U.S. motion picture industry (*Motion Picture Investor,* Paul Kagan Associates, January 22, 1990, p. 2).

[29]*Cable TV Investor,* Paul Kagan Associates, November 30, 1989, p. 5.

AN INTEGRATED NETWORK WITHOUT SWITCHED VIDEO

The preceding analysis suggests that, in the absence of a strong demand for switched video, the company would build two networks (with coordinated construction) because the additional cost of building an integrated network to provide switched video would fall short of the additional revenues from that service.

However, another possibility arises. The savings from not offering switched video on the IBN could conceivably be large enough that the cost of the IBN without this service could fall below the overall cost of the two separate networks. If so, the company would prefer the IBN to separate networks. To assess this possibility, we estimate the costs of our active double star base case, but with the switched video capability deleted. Our estimates, displayed in Appendix D, show that the investment cost of an IBN without switched video would be $1449, compared with $1760 for a switched IBN with 1.5 hours per week of on-demand video per subscriber—a saving of $311 per home passed. The separate networks are still cheaper.[30]

This result should not be surprising. It simply reflects the fact that the tree and branch architecture used today by cable operators is an effective mechanism for distributive video. Moreover, a separate video delivery system permits use of analog signals to the home, fully compatible with existing analog TV sets, while a digitized system requires special conversion devices in (or near) the home. In contrast, efficient delivery of switched services calls for some variant of a star network. Trying to combine the two in a single system can actually add to costs.[31] Contrary to the implications of some of the descriptions in the literature about fiber to the home, there is nothing magic about services "integration." Whether integration makes sense depends on the facts at hand.

SUBSIDIZATION OF SWITCHED VIDEO

Our analysis suggests that, in the absence of a strong demand for switched video, the telephone company would prefer to build two net-

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[30]O&M costs, as well as investment costs reported above, must be considered in determining whether the separate networks cost less than the IBN. As we argued above, there is no reason to believe that O&M expenses for the IBN, as a percentage of investment, would fall below those for separate networks.

[31]Our conclusion is based on the assumption of a fully residential service area. The presence of business users in the area who require broadband services might facilitate the integration of services over one network.

works (with coordinated construction) rather than the IBN postulated in this study. Thus, the outcome of abolishing all legal restrictions to the entry of the telephone company into the delivery of video signals would be to give it control over both a cable TV network and a (separate) narrowband network, with essentially the same services as those available today. Benefits to society would accrue through the lower costs afforded by use of fiber, but these benefits would not depend on abolition of restrictions on market entry.

The emergence of two separate networks with no switched video service is based on the presumption that the telephone company seeks to minimize cost for any given level of output. This situation has nothing to do with whether the company could "afford" to build an IBN *with* switched video. If it had to either confine itself to narrowband services or build an IBN *with* switched video it might well choose the IBN. By raising the prices for its distributive video services—facilitated by the absence of competition from an incumbent cable TV operator—it could, in effect, subsidize its on-demand services and total revenues might exceed total cost. Overall profits could well be higher than those from narrowband services alone, leading the telephone company to choose the IBN.

But an all-or-nothing choice is not the issue (nor should it be) in the current policy debate. Rather, the issue is whether telephone companies should be allowed to deliver video services. Our analysis suggests that, if given that freedom, the telephone company would offer essentially the same video services as those available today. It would likely not offer switched on-demand service because the incremental revenues from the service would probably not cover the incremental costs. Nor would it be in society's interest for the company to offer on-demand service, unless a persuasive argument could be made that subsidization of this particular service by other telecommunications services would, on balance, benefit society.

III. OTHER NETWORK ARCHITECTURES

The active double star network is only one of several alternatives for delivering integrated broadband services. Would others be less costly than the one we have postulated in the base case? Let us consider first the "passive" double star.

PASSIVE DOUBLE STAR

In some applications, this architecture involves lower investment costs than the active double star, as treated in Appendix A, in part because the RDU has no switching capability. The RDU is closer to the subscriber, serving only to split the optical signal carried from the central office into individual signals to each home. The network is termed "passive" in that no power is required to operate the RDU. For example, suppose that 12 channels are fed from the central office to the RDU which, in turn, serves 12 homes as illustrated in Fig. 2. All homes have access to the 12 channels because the RDU simply sends all of them to each home. But, in effect, each home has a dedicated channel from which it can select any distributive or on-demand program through the switch at the central office.

Because the channel is dedicated, the cost of transmission is not affected by subscriber demand. Unlike our base case, network costs are constant regardless of whether the subscriber requests one or ten videos per week.[1]

Costs, computed under the same ground rules as those in Table A.2, are shown in Table 11 for an assumed 60 percent video penetration. The passive double star is moderately superior and would look even better at higher levels of on-demand video. But it has one key drawback: Dedicated channel capacity is limited to 50 Mb/s, which is insufficient for HDTV at anywhere near its current state of development. This is a potentially serious handicap because the competitive cable TV system could probably be configured without great difficulty to handle HDTV.

What would be the additional cost of upgrading the passive double star to handle 150 Mb/s channels for HDTV, comparable to those in our base case? Wavelength division multiplexing systems (WDM)

[1]However, the level of demand would affect the costs of the jukebox, which we take into account for the varying demand levels shown in the preceding tables.

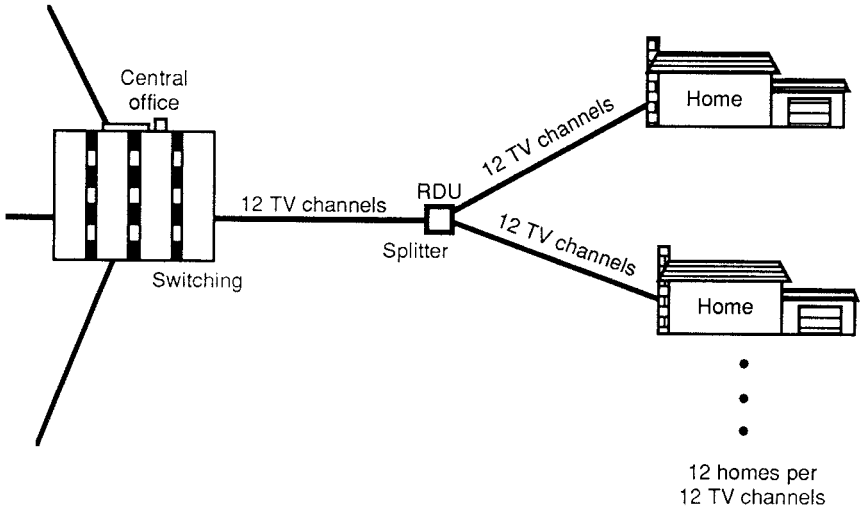

Fig. 2—Passive double star network

Table 11

COMPARATIVE ANNUALIZED INVESTMENT COST PER HOME PASSED, 1.5 HOURS AVERAGE ON-DEMAND VIEWING PER WEEK
(In dollars)

% On-Demand Video Penetration	Active Double Star	Passive Double Star	Switched Star
40	327	276	346
60	343	288	389
80	358	302	474

would have to be perfected to increase by threefold the transmission rate.[2] This technology is still in laboratory development, and

[2]The difficulty in simply increasing the 622 Mb/s signal to the 1.866 Gb/s signal that would be necessary to carry HDTV is the increased cost in electronics. Cheaper silicon-based semiconductors would give way to higher-cost gallium arsenide semiconductors placed in the equipment at each subscriber's home. Thus, a digital bus approach (a bus in the sense that all channels are time division multiplexed together into a single bit

uncertainty remains as to when it will be available at an attractive cost for this application.

An additional complication is that successful development of WDM technology could also have a favorable effect on advanced cable TV networks, so that the *incremental* costs of adding on-demand video capacity would not be as favorably affected as one would otherwise conclude.

SWITCHED STAR

In contrast to the passive double star, this architecture offers a dedicated *fiber* rather than a dedicated (50 Mb/s) *channel* from the central office to the home, illustrated in Fig. 3. Thus, it would easily handle

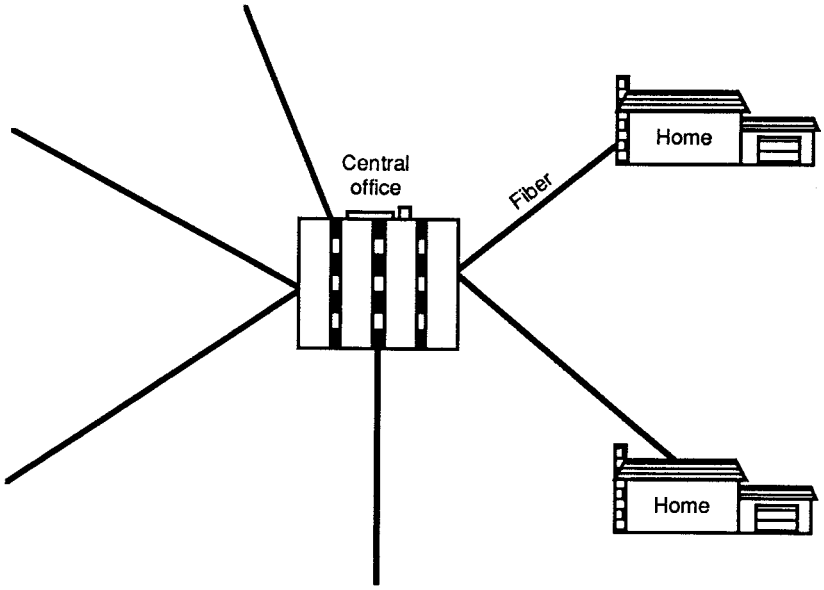

Fig. 3—Switched star network

stream) is not yet feasible for high-capacity systems that would expand the capacity of the passive double star architecture to equal that of the active double star, which would be sufficient for HDTV. Consequently, Wagner and Lemberg (1989) and Faulkner et al. (1989) have proposed a WDM-based system.

HDTV and, as with the passive double star, costs would be insensitive to volume of demand. However, this architecture is more costly than the active double star.

In conclusion, the active double star holds up well against these alternatives. At the same time, much thought and experimentation is being devoted to variants of these alternatives, so that one cannot dismiss the possibility of breakthroughs going beyond the limits of our analysis. Especially if attractive ways can be found to increase the capacity of the passive double star to handle HDTV, this architecture might be superior to that in our base case.

ALTERNATIVE NARROWBAND NETWORKS

In addition to the above broadband networks, we explore two alternatives for narrowband service: an all-fiber network and a "fiber-to-the-curb" network. Our purposes are to determine whether cost savings are possible over the copper/fiber narrowband hybrid treated in Sec. II, and to lay the foundation for assessing possibilities of network evolution from narrowband fiber to the curb to broadband service addressed in Sec. V.

All-Fiber Narrowband Network

The cost of an all-fiber network, discussed in Appendix F, is shown against alternatives in Table 12. Despite the substantial cost reductions we assume for fiber components, the all-fiber network is substantially less attractive than the copper/fiber hybrid. Indeed, the annualized cost exceeds that of the hybrid narrowband and the hybrid cable television networks combined, shown in Table 6.

It is not difficult to understand why the costs of an all-fiber network are so high. Large differences arise in the remote distribution unit, in the distribution loop, and in equipment at customers' homes. The last component is notable in illustrating the costs of powering and converting from digital/optical to analog/electrical in or near the home. Conventional analog telephone service in the copper/fiber hybrid involves no special electronics in the home.

Fiber to the Curb

Another possibility involves a much higher degree of common plant in the distribution loop. One approach, known as "fiber to the curb," would bring fiber to the pedestal shared by several users, similar to

Table 12

COST OF NARROWBAND NETWORKS
PER HOME PASSED
(In dollars)

	Copper/ Fiber	All Fiber	Fiber to the Curb
Investment	568	1164	679
Annualized cost	93	196	114

that shown in Fig. 1.[3] The optical network interface (ONI) would be installed in the pedestal and conventional copper drops would bring signals into the home. This architecture stands in contrast to the copper/fiber hybrid where the ONI would be placed in the RDU and copper (rather than fiber) would be installed from there to the home. Although the investment cost of $679, in Table F.3 and Table 12, is far below that of the all-fiber narrowband treated above, the figure exceeds the estimate of $568 for the narrowband hybrid in Table 12. Whether common plant savings will eventually make fiber economically superior to copper is the subject of much current debate.[4] In any case, during the time horizon of our study, either all-fiber or fiber-to-the-curb networks appear more costly for narrowband capability and offer no greater variety of services than could be delivered over the copper/fiber hybrid.

[3]For example, one telephone company representative has concluded that "We don't think fiber-to-the-home makes sense . . . . Fiber to the pedestal is the step that we at Ameritech intend to take," *Multichannel News,* November 1989, p. 28. This view is shared by four other Bell operating companies, "BOC's say fiber-to-the-home not feasible," *Multichannel News,* January 29, 1990, p. 30. In Appendix F, we assume that the pedestal would serve eight homes. Typically, the pedestal would consist of a buried or above-ground cabinet near the homes.

[4]No comprehensive study has yet been done that includes cost changes to identify an economic crossover. Some studies that predict a crossover to fiber within the next few years suffer from incomplete explanations and dubious assumptions (e.g., the only cost component that is assumed to increase is copper cable at a rate of 5 percent per year).

IV. COMPETITION AND GOVERNMENT REGULATION

We have said nothing about the potential response of cable operators to entry by telephone companies or about the effects of government regulation of telephone rates. Continuing our analysis involving large new communities, we ask:

- What are the prospects for a cable operator entering the market, given that the telephone company moves first?
- How would the telephone company respond if, contrary to the above, the cable operator moves first in providing video services?
- Which entity is likely to move first?
- Under what conditions would the two entities merge?
- How would government rate regulation of telephone services affect outcomes?

COMPETITION WITH CABLE TELEVISION OPERATORS

Once the telephone company provides video service as we have discussed, is a cable operator likely to enter the market? The answer is almost surely no. The situation is no different from that of a prospective cable entrant facing an incumbent cable operator. Given the strong economies of scale and scope for construction of facilities for television delivery, the industry has the characteristics of a natural monopoly.[1]

Few instances of "overbuilding" have occurred, i.e., two cable companies standing ready to serve the same households.[2] Threats by a

[1]For a survey of empirical studies on the economies of scale in cable television see Besen (1985). The bleak prospects for overbuilding are discussed in *Multichannel News*, April 13, 1987, p. 17. In contrast, Hazlett (1990, p. 66), concludes that "the difficulties faced by competitive entrants arise not so much from natural monopoly conditions as from the ability of incumbent suppliers to transfer monopoly rents to municipal officials so as to protect their exclusive franchise." If Hazlett is correct, the obvious solution is to abolish municipal entry barriers. Elimination of the crossownership ban, on top of abolishing local entry barriers, would not greatly add to competitive pressures because telephone companies, according to our analysis, have no special economic advantage over cable operators in entering the residential video market.

[2]One of the most notable exceptions is in Allentown, Pennsylvania, where two cable operators compete side by side. The reasons are poor over-the-air reception (resulting in a penetration level near 100 percent) and high housing density (reducing the cost per home of laying duplicate lines).

prospective entrant commonly are empty or are followed with a buy-out. In either case, only a single firm survives in a given geographical area.

To understand better the conditions under which competition *would* be feasible, consider the counterfactual case: Suppose that the costs of constructing and operating trunk, feeder, and distribution lines were very low—so low that the additional cost of installing parallel lines is very small relative to differences in service diversity, quality, and price offered by alternative suppliers. Subscribers, with their own drop lines and equipment in the home, would then be free to "hook in" to the competitive suppliers of their choice. The salient characteristic of viable competition here is that the cost of market entry—embodied in trunk, feeder, and distribution lines—is low.

But our estimates—and industry experience—do not suggest that the cost of market entry is low, with or without fiber options.[3] Some cable operators are beginning to install fiber in their trunk lines to reduce maintenance costs, increase capacity, and improve the quality of service, as discussed above. Telephone companies are installing fiber in their feeders for straightforward economic reasons. However, nothing we have seen in the literature suggests that the costs of market entry will fall to the point where we will see widespread side-by-side competition in the foreseeable future.

The preceding is based on the presumption that the telephone company moves first. But suppose that the cable company is able to install its system while the telephone company plant is still in the design phase. Would the telephone company proceed to offer a competitive video service? The answer is again no. The problem for the telephone company is that there are no economies of scope in combining switched narrowband and distributive video services in an IBN. As we demonstrated in Sec. II, the company saves money by installing separate switched narrowband and distributive video networks because of differences in preferred network architectures for switched and nonswitched services.[4] Thus, the telephone company would face the same situation

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[3]The high cost of entry and lack of competition lead some to advocate that cable channels be made available on a common carrier basis as a possible way to stimulate competition among program suppliers. But a common carrier, or leased access, approach faces difficulties of shutting out those program suppliers unable to pay common carrier access rates but able to pay their lower incremental cost of access. In contrast, a cable operator free to engage in price discrimination among program suppliers would have an incentive to provide access to these suppliers. See Besen and Johnson (1982).

[4]In contrast, there *are* economies of scope in combining distributive video services. Thus, a cable company can much more cheaply provide basic service, pay movie channels, and pay-per-view service on the same network than would be the case if each were offered on separate networks. Similarly, economies of scope arise in switched narrowband services, e.g., voice, facsimile, and data.

as a prospective cable television entrant. Construction of a cable television network alongside its narrowband system would not be attractive for the reasons noted above.

In summary, the above outcomes involve two networks: one for switched narrowband services, the other for distributive video. If the telephone company moves first, it owns both.[5] Otherwise the telephone company confines itself to narrowband services. In the latter case, the two entities might merge as elaborated on below.

One other possibility merits attention. Suppose that the cable television company moves first, while the demand for *switched* video becomes very strong. The telephone company might build the IBN because of the lucrative switched-video market. The incremental cost of adding distributive video to the network might be low enough to enable the telephone company to offer video service in competition with the cable incumbent. However, competition might not be sustainable in the long run. With sufficiently low incremental costs for distributive video the telephone company could price the service so that the cable company, to meet this price, could not recover its total cost including its plant investment. If so, it would continue operating so long as it covers its variable costs but would shut down when its plant needs replacement. In the meantime, a single entity might acquire both facilities to obtain a monopoly of distributive video service.

WHICH ENTITY MOVES FIRST?

Since it is likely that only the first mover will supply video, does either entity have an advantage over the other in being able to move first? We suggest that two factors are relevant to the answer—whether any asymmetry exists in the need for or conditions of a local franchise, and whether the telephone company can subsidize its planned video services from revenues collected from telephone users.

Asymmetries in the Local Franchising Process

Recall our basic assumption noted in Sec. I that all legal bars to telephone delivery of television signals are eliminated. Thus, the telephone company that holds the franchise for telephone service within the territory where our hypothesized new community is located would be free to offer video service. In comparison, cable operators face two possibilities. First, the new community may be in an area for which no

[5]More precisely, it would have the option of owning both. Having built the two networks, it might decide to sell the video network to another entity.

cable operator holds a franchise. The process of awarding a franchise (either on an exclusive or a nonexclusive basis) by community officials could be a source of delay, enabling the telephone company to move first. Second, the new community may be within a territory for which a cable operator already holds a franchise. Two subcases arise here.

- The cable operator faces obligations under the franchise agreement, such as paying a percentage of revenues as a franchise fee, and making available channels and equipment for government and other specified users. If the telephone company has no such obligations, it may be in a better position to move first, especially if disputes arise between the cable operator (or prospective cable operators if the franchise is nonexclusive) and the franchising authority about the terms of the franchising agreement.
- The cable operator faces no obligations under the franchise that place it at a competitive disadvantage against the telephone company. In this case, our analysis sheds no light on which entity moves first.

In the current debate about telephone company entry into the video market, concern has been expressed that the two entities will not be on a "level playing field" because of differences in the need for and the terms of the franchise. The above highlights the relevance of that concern. It seems clear that, *for comparable services,* telephone and cable companies should be positioned equally with respect to franchising requirements.

The Possibility of Cross-Subsidization

The assertion is commonly made that telephone companies can offer competitive service at below cost and compensate by raising rates to their monopoly telephone ratepayers. If so, they might have an advantage in moving quickly into a newly developed community to foreclose entry by a cable operator. The leeway afforded by the additional financial support (even though a cable operator might also be financially strong) could confer a competitive edge in procuring hardware and beginning installation, which would need to be coordinated with the developer of the new community.

We treat the issue of the cross-subsidies later. It is worth nothing here, however, that in a close race for market entry—where the telephone and cable companies are on equal grounds in terms of franchise requirements for video delivery—only a small amount of cross-subsidization might suffice to tip the balance in favor of the telephone company.

INCENTIVES FOR MERGERS

As discussed above, if the telephone company moved first it would be the sole provider of both narrowband and broadband service. If the cable operator moved first, separate entities would supply the two services. In the latter case, however, one entity might buy out the other for either of two reasons. First, some economies might be afforded by a single entity installing and operating the two systems. For example, the costs of maintenance crews may be reduced if they were integrated into a single organization. Savings might also accrue in office and other administrative functions.[6]

Second, a merger would preclude whatever competition would otherwise occur between the two systems. Although competition in the video market is unlikely for the reasons previously discussed, other possibilities arise. For example, cable companies might use their unswitched broadband networks to compete in certain voice and data markets. An example involves cable companies offering large business users unswitched voice and data channels to bypass local telephone facilities for direct access to long-distance carriers. Moreover, using downstream video with their upstream data capabilities, cable operators might develop information services (including still-frame video displays of data and pictures) in competition with information services provided by the telephone company. Although such applications are of little significance today, they could grow during the decade to raise concerns about the desirability of mergers between telephone and cable companies.

GOVERNMENT REGULATION AND ANTICOMPETITIVE BEHAVIOR

Except for brief reference to cross-subsidization above, we have treated the telephone company, in effect, as if it were unregulated. We would expect it to seek to maximize profits and, in the absence of regulation, it would attain this objective by operating efficiently, i.e., by minimizing the cost of producing any given output.

The pressure of regulation, however, can perversely affect the incentives of the firm. The "cost-plus" nature of traditional rate-of-return regulation in telecommunications, electric power, and other utilities has been of long-standing concern to regulatory agencies, legislatures,

[6]However, there is reason to believe that such savings, while worth noting, are not likely to be large. Telephone and cable companies could today enter into cooperative agreements covering maintenance and other functions without violating the crossownership ban. The fact that such agreements are rare suggests that potential cost savings would be small. Of course, the use of new technologies may affect the economics of cooperation.

consumer groups, and others. As long as the rate-regulated firm can pass on to customers whatever additional costs it incurs, and must also pass on whatever cost savings it achieves, its incentives for efficient operation are blunted.

Many assert that, under these circumstances, telephone companies are in a position to subsidize their competitive services at the expense of their monopoly telephone ratepayers. Under rate-of-return regulation, the threat exists of the company passing some of the costs of its nonregulated services back to its regulated sector. This possibility arises because of the problem of allocating to individual services the costs of facilities that they share in common. Thus, a telephone company might allocate (in ways difficult for regulators to detect) portions of its fiber plant to basic telephone subscribers, resulting in higher telephone rates than would arise if the telephone company did not offer video service. This action would discourage entry by competing video suppliers using, for example, direct broadcast satellites or terrestrial microwave transmission. Moreover, as discussed above, this action might enable the telephone company to move first in large new communities to foreclose entry by a cable operator.

A large literature has been directed to issues of conditions under which the firm would find it worthwhile to engage in such predatory pricing—an area complicated by the fact that controversy exists about the standards that are appropriate for determining the presence of predatory pricing.[7]

A large literature also addresses the problems posed by rate-of-return regulation for efficient behavior of firms, and the possible use of price caps and other forms of "incentive" regulation for reducing the perverse effects associated with rate-of-return regulation.[8] Typically, under price caps groups of services are divided into separate "baskets." Each basket has a price ceiling computed as the weighted average of prices of services within the basket. An inflation adjustment is included to permit the ceiling to rise over time, while a productivity adjustment forces the cap downward to reflect increases in the firm's productivity. A formal review is conducted at specified intervals to

[7]Some argue that, for a number of reasons, predatory pricing is rare, if it exists at all. For this point of view see Esterbrook (1981) and McGee (1980). Others construct situations in which predatory pricing is a plausible outcome, e.g., Ordover and Saloner (1989). The appropriate standards for detecting the presence of predatory pricing are treated, for example, by Areeda and Turner (1975), Brodley and Hay (1981), Joskow and Klevorick (1979), Ordover and Willig (1981), and Williamson (1977).

[8]See, for example, Beesley and Littlechild (1989), Braeutigam and Panzar (1989), Brennan (1989), Brown et al. (1989), Johnson (1989), Lewis and Sappington (1989), Schmalensee (1989), Sibley (1989), Vogelsang (1988), and Vogelsang and Finsinger (1979).

revise the plan in the light of experience, possibly including changes in the inflation and productivity factors.

Recognizing the problems associated with rate-of-return regulation, numerous states are moving toward various forms of price caps or profit sharing schemes where earnings above specified levels of rate of return are split between the company and consumers.[9] These approaches are designed to strengthen companies' incentives to operate efficiently by permitting them to keep at least a portion of whatever additional profits they reap by reducing costs for given levels of outputs. Most notable for purposes here, a well designed price cap plan would reduce the incentives to engage in predatory pricing because losses in contested markets could not be absorbed by simply hiking prices to telephone customers.[10] Use of price caps would make such price increases more difficult. Losses incurred in the contested market would result in a reduction of the firm's retained profits. Of course, only experience will show how well such plans now being widely adopted will improve the operations of regulated firms.

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[9]For recent developments in a half dozen states within the territory of U.S. West, see *Telecommunications Reports,* December 11, 1989, pp. 12–13. Developments elsewhere, such as the notable regulatory programs in California, New York, and Vermont, are reported regularly in this and other industry newsletters.

[10]Properties of a "well designed" price cap system are discussed in the references in footnote 7, above. An independent assessment of price caps and other regulatory regimes is beyond the scope of this study.

V. SERVICE TO EXISTING RESIDENTIAL AREAS

In the preceding, we considered only a large new residential community where all telecommunications investments were yet to be made. We concluded that separate narrowband and broadband networks would be less costly than an IBN and that the broadband network would be owned by either the telephone company or the cable operator, depending on which one moves first. Merger of the two entities is also a plausible outcome.

Here we consider existing communities already served both by the telephone company with a conventional narrowband network and by a cable operator with broadband service. We will show that telephone companies would face severe difficulties in seeking to provide video service because of competition from incumbent cable operators and the piecemeal character of new residential construction. Moreover, although some argue that telephone companies would cross-subsidize to enable them to compete in the video market, the amount of cross-subsidy required would be huge and easy for government regulators to detect.

COMPETITION FROM INCUMBENT CABLE OPERATORS

Cable systems already serve more than 50 percent, and pass more than 80 percent, of the nation's homes. The wide variety of existing basic and pay cable services, and the dubious prospects for switched video services, do not bode well for telephone company entry.

Difficulties for telephone companies would be compounded by the fact that the same technological advances that enhance fiber's attractiveness to the telephone companies would also enhance its attractiveness for cable systems. As noted above, some cable operators are already retrofitting their backbone trunk lines with fiber. This reduces the number of amplifiers in cascade, thereby improving signal quality by reducing noise and cutting maintenance costs. This trend will continue as the technology advances.

This process favors the cable operator. The use of fiber in the feeder lines *immediately* improves video service to downstream subscribers, since they are already attached to the network by broadband coaxial cable. But fiber installation in the telephone company's feeders

does not, by itself, provide *any* video service to telephone subscribers because they are connected to the network only with narrowband copper lines. Thus, the cable operator can progressively retrofit portions of the plant, simultaneously improving quality of service, while the telephone company would face an awkward and potentially expensive cutover to bring video down the last link to its telephone subscribers.

In the absence of a strong demand for switched video, the telephone company would likely not cover the costs of offering video in competition with the cable incumbent. Without a strong switched video market, the telephone company would be in much the same position as an outside cable operator seeking to decide whether to enter the market against an incumbent. For the same reasons discussed in Sec. IV, the prospects for successful competitive entry would be bleak. Thus, either in existing communities or in new communities the "two-wire" competitive scenario depicted in Sec. I is an unlikely outcome. In existing communities, either incumbent cable operators will remain sole suppliers of video or they will merge with telephone companies for the reasons discussed in Sec. IV.

PIECEMEAL NATURE OF NEW RESIDENTIAL CONSTRUCTION

It is easier to install fiber to new homes, free of existing telecommunications investments, than it is to retrofit. For this reason, we started with the case of a large new community. Because new construction increases the number of new households from 1.5 percent to 2 percent annually, one might conclude that perhaps as many as 20 percent of U.S. households might be served by telephone service over fiber by the year 2000.[1]

But such a calculation is misleading because of the piecemeal character of new housing construction. Consider, for example, a new house constructed on a vacant lot among existing dwellings. Even if fiber is being used in the feeder, as is done with digital loop carrier, the telephone company would find it uneconomic to run new fiber in the distribution network only to the new dwelling, while continuing use of the existing copper plant to the rest. Fiber service separate from existing copper service will probably be attractive only for a new residential development large enough to be served by new distribution lines from existing or new central offices.

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[1]Pepper (1988), p. 16.

In short, incorporating fiber into existing copper networks will not be easy. One option is to build new fiber alongside existing copper plant and (perhaps overnight) switch service from the old to the new for a whole neighborhood or community served by the central office. Inevitably, there will be some waste as still valuable copper lines are replaced. Thus, it is not enough that a fiber network be as cheap as a copper network. It must reduce costs enough to justify junking portions of the existing copper plant.

The problem is compounded by the fact that fiber will be of little benefit to basic telephone subscribers. To be sure, some subscribers with very long runs to the central office may today experience noise that would be eliminated by the substitution of fiber.[2] But, by and large, subscribers will only be inconvenienced by the switch-over.

Another option—"fiber to the curb," treated in Sec. III—extends fiber into the distribution loop (as old loops need replacement) as far as the pedestals shown in Fig. 1. The company could then run coaxial cable and copper twisted pairs to the home for broadband and narrowband services, respectively. An advantage of this approach lies in reducing disruptions associated with installing fiber by keeping the cut-over point outside the customers' homes and keeping the provision of emergency power in the hands of the telephone company. Since power cannot be conducted on fiber, separate copper electric power lines would need to be installed (along with backup batteries) in the pedestals.

The major potential disadvantage is that the pedestal may need environmental protection for switched broadband electronics, as discussed in Sec. II. If so, capital costs would rise by hundreds of dollars per subscriber.

CROSS-SUBSIDIZATION AND NETWORK EVOLUTION

The argument is frequently advanced that telephone companies can subsidize their competitive ventures by hiking rates to their telephone customers, as discussed in Sec. IV. Accordingly, the question arises as to whether the telephone company could subsidize its video services to compensate for the disadvantages depicted above. We conclude that the leeway for cross-subsidization would be limited because the nature and levels of the required cross-subsidization would be such that government regulators (and the public) would intervene.

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[2]However, service to these subscribers is already being improved by installing fiber in the feeder, without bringing fiber all the way to the home.

A Hybrid Cable Network

Recall that the cheapest way to provide distributive video is with a hybrid fiber/coaxial cable network as described in Appendix G. For this reason, the telephone company might seek to compete with an incumbent by building such a cable network.

However, the latitude for cross-subsidization would be limited because the costs of building a cable network alongside the company's existing narrowband network could easily be identified for purposes of regulatory treatment. The area of potential regulatory difficulty would involve the terms of access by the new cable affiliate to ducts and poles owned by the telephone company. One solution is to require that access be under the same terms and conditions as that accorded to the competing cable company. To be sure, this would not be a perfect remedy because controversies would surely arise about what constitutes "equal" treatment. But it is hard to imagine that the leeway for discriminating against a cable operator with facilities already installed would be sufficient to overcome the competitive disadvantages faced by the telephone company.

This conclusion is reinforced by the likelihood that the telephone company would face increased scrutiny if it embarked on a strategy of essentially duplicating the cable plant already in place. As discussed in Sec. I, the telephone companies' case for abolishing the crossownership ban rests on bringing fiber to the home for improved or new services that cannot otherwise be provided. If, instead, they attempt to compete with cable operators with the same kinds of networks and services, disillusioned regulators and the public would become especially watchful that telephone customers did not end up paying the bill.

An Integrated Broadband Network

A second possibility is to construct the more costly IBN. The primary advantage of doing so—in terms of successful cross-subsidization—is that separation of cost by service would be more difficult because of the greater sharing of common facilities. However, this strategy is not promising because the amounts of required cross-subsidization would be large and easy to detect.

To illustrate, suppose that the telephone company embarks on an evolutionary network strategy to bring fiber progressively closer to the home for narrowband service, eventually extending fiber to the curb. Subsequently, the firm retrofits the network for broadband service. Suppose, further, that the company is permitted by regulators to build the narrowband fiber-to-the-curb network despite the fact (shown in

Table 13

INVESTMENT COST OF ALTERNATIVE NETWORKS PER HOME PASSED
(In dollars)

	IBN Switched Video[a]	IBN No Switched Video[b]	Cable Television Hybrid[b]	Narrowband Hybrid	Narrowband Fiber to the Curb
Electronics	1311	1015	167	287	413
Nonelectronics	449	434	201	281	266
Total	1760[c]	1449[d]	368[e]	568[f]	679[g]

[a]60 percent video penetration, 1.5 hours on-demand video per week per subscriber.
[b]60 percent video penetration.
[c]Table D.1.
[d]Table D.1.
[e]Table G.2.
[f]Table E.1.
[g]Table F.3.

Table 13) that it is more costly than the copper/fiber hybrid treated in Sec. II, while offering nothing beyond the service available on the hybrid.[3] We might imagine that the telephone company persuades regulators that fiber promises to support enough new or better services to justify the added cost burden on telephone subscribers.

With fiber available at the curb, the issue then arises about the cost of upgrading to broadband capability. Two questions are relevant: (a) Can electronics be upgraded easily by simply adding components, or would previously installed electronics have to be replaced? (b) Could additional fiber required for broadband be installed easily, i.e., at the same incremental cost as if it had been installed at the time of the progressive conversion from copper to fiber narrowband? We will assume that the upgrade is easy to facilitate the use of our previous cost estimates, shown in Table 13, in a crude analysis of the incremental costs of network evolution. To upgrade the fiber-to-the-curb system to the IBN with no switched video (i.e., to provide essentially the same

[3]The estimates in Table 13 are not entirely satisfactory, since they are based on new construction in new communities as treated in previous sections of this study. In contrast, here we consider new networks as retrofits of existing ones. However, only *differences* in costs shown in Table 13 are relevant to the analysis here. Generally, these differences are less affected than are total costs by a shift in analysis from new communities to existing ones. A notable exception is that cost of the narrowband and broadband hybrids would be lower than the figures shown because the hybrids would use the coaxial cable and twisted pairs already in place for broadband feeder and narrowband distribution lines. This reduction would further increase the incremental cost of upgrading to an IBN.

service offered by the competing cable operator) would involve incremental electronics and nonelectronics investments of perhaps $602 and $168, respectively, for a total of $770.

Suppose that to compete with the incumbent cable operator (who is assumed to have the same technology as the hybrid cable system in Table 13) the telephone company would be forced to cover no more than $368 of the $770 from video revenues. The remaining $402 would need to be covered by revenues from narrowband services—a figure that *by itself* exceeds the cost of a separate cable network. It is most difficult to imagine regulators allowing such a large cost shift to telephone users.

As a variant of the above, suppose that the telephone company installs the additional fiber and other nonelectronic plant required for an IBN without switched video, at the time it is building the fiber-to-the-curb narrowband network, and is able to justify the action to regulators on the basis of expected telephone traffic growth. Although telephone users would be burdened with the extra cost of $168 ($434 – $266 from Table 13), the company would still face the large and visible task of upgrading the electronics. It remains difficult to imagine regulators allowing the cost burden of $234 ($402 minus $168) to be shifted to telephone users.

In response, some might argue that the upgrade would be delayed to take advantage of technological advances that would reduce costs below our estimates—perhaps during the early part of the next century. However, this strategy of pushing the time frame into the next century raises two problems. First, intervening technological advances will benefit the narrowband hybrid and the cable hybrid networks as well. Thus, the *differences* in cost, which are key to our analysis, would be affected less than one might expect by examining only the effects on IBNs. Second, telephone companies will face progressively stronger competition. Cable operators will continue to install addressable converters to expand the availability of pay-per-view service; the use of video cassette and disc players will probably increase along with video rentals and sales; and it is not out of the question that direct broadcast satellites will emerge as powerful competitors in delivering television programs to the home.

Mechanisms for Regulatory Control

The task of regulators would be eased by using as a benchmark the least-cost way of providing narrowband services. Recall that in our analysis in Sec. II we subtracted the cost of a fiber/copper narrowband network to obtain the incremental cost of video services. Regulatory

agencies could do the same to reduce the possibilities of cross-subsidization, perhaps as part of a price cap program.[4] Narrowband users would be burdened with no more than the cost of a "stand-alone" narrowband system.[5] The telephone company would be left to cover its incremental costs of video service from video revenues.

To be sure, this process cannot be expected to work with precision. Controversy would arise about the "least cost" or "reasonable" cost of narrowband service, especially since costs are strongly dependent on individual circumstances. But even crude measures would probably suffice to preclude the large cross-subsidies that would be required for telephone companies to compete successfully with incumbent cable operators.

Concluding Remarks

Three final points warrant emphasis.

- Of critical importance is the cost of upgrading the narrowband plant to broadband capability. For example, according to our estimates the cost of upgrading a narrowband fiber-to-the-curb network to provide nonswitched video would exceed the cost of a separate hybrid cable television network.
- The above analysis highlights the importance of switched video or other broadband services that would not be provided by cable operators. If revenues exceeded the incremental costs of switched broadband services computed in Sec. II, the prospects for competitive entry by telephone companies would be improved.
- This analysis of cross-subsidization must be distinguished from that in Sec. IV. There we concluded that cases might arise where a small amount of cross-subsidization could tip the balance in favor of the telephone company in a close race to enter a new market ahead of a cable operator. That degree of cross-subsidization might be difficult for regulators to detect and prevent. Thus, we conclude that the strongest prospects for cross-subsidization lie in large new communities, not in communities where cable television systems already exist.

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[4]Under a price cap program narrowband services could be put in one or more baskets separate from video services. The caps for narrowband services, productivity adjustments, and the periodic formal review of the price cap plan would be based on the costs of the narrowband stand-alone system.

[5]For a discussion of tests for detecting cross-subsidy, see Faulhaber (1975).

VI. PUBLIC POLICY IMPLICATIONS

The apparently bleak prospects for telephone companies attempting to compete with cable TV companies for television delivery, or for development of new services, might lead some readers to conclude that the existing crossownership restrictions should be retained. Without clearly perceived benefits to consumers no basis exists, one might believe, to change the status quo.

However, we cannot recommend, on the basis of this study alone, whether the ban should be retained or abolished. Several factors, in addition to video competition and development of new services, must be considered in reaching an overall judgment. Weighing in favor of abolishing the ban are factors relating to R&D activities and to potential cost savings from merged narrowband and broadband activities. Weighing against abolishing the ban are factors relating to potential anticompetitive concentration of information sources and to possibilities for cross-subsidization. Moreover, questions arise about the degree of freedom that should be accorded to telephone companies, involving issues of diversity of voices and First Amendment protection.

POTENTIAL BENEFITS OF ADDITIONAL R&D

Removal of restrictions might stimulate socially desirable R&D for at least three reasons.

- Telephone companies have a different history of technological development than do cable TV systems. The approaches they might take to broadband fiber R&D might vary from those of cable operators, possibly leading to unanticipated breakthroughs. For example, concentration on network architectures such as a passive double, or even triple, star as an alternative to the active double star in our base case, may lead to more favorable outcomes than we describe. The history of R&D is replete with cases where final outcomes resulted from the winnowing out of early, different approaches to problem solving.
- Broadband R&D might favorably affect other lines of telephone company business. Especially, spillovers could reduce the cost of basic telephone service, as illustrated in the differences between the current and future costs we estimate for copper/fiber hybrid narrowband networks.

- Additional broadband R&D, even if it leads to no useful results, might put competitive pressure on cable operators to reduce prices and improve service.

Although a number of telephone companies are experimenting with integrated broadband networks, it is not likely that they will fund substantial levels of R&D without assurance of being legally permitted to enter the market.[1] To be sure, the FCC's crossownership rules permit them to provide video on a common carrier basis. But, as noted in Sec. I, the Cable Act stipulates that even on this basis a local franchise is required by program suppliers (unlike the case of data and voice).

COST SAVINGS FROM MERGERS

As discussed in Sec. IV, cost savings might accrue from integrated maintenance and administrative functions for telephone and cable television networks. Although we concluded that the potential savings would likely be small, they must be included as a potential benefit of lifting the ban.

ANTICOMPETITIVE CONCENTRATION OF INFORMATION SOURCES

The flip-side of the potential benefits of mergers is the potential anticompetitive concentration of information sources. Although we conclude that competition in the video market is, in any event, unlikely, we have noted other possibilities of competition between telephone and cable companies. The problem faced by policymakers here is no different from that in other industries (e.g., the airlines). One can point to potential cost savings and other efficiencies of merged operations, and can at the same time be concerned about the potentially undue concentration of power.

CROSS-SUBSIDIZATION

We have concluded that cross-subsidization, if it arises at all, would most likely occur in a large new community where telecommunications facilities are yet to be built. At the same time, the prospects are remote that telephone companies will be able to cross-subsidize to the

[1]An especially detailed account of one such experiment—in Cerritos, California, with involvement by GTE—is provided by Dutton and Bywater (1989).

degree needed to overcome the handicap they would face in competing with existing cable television systems.

This area clearly needs further evaluation. Leading questions include: Under what conditions would telephone companies have incentives to engage in large-scale cross-subsidization to support risky new activities at the expense of telephone users? Will price caps and other reform measures now being widely adopted reduce the potential for cross-subsidization? If a telephone company proposes to construct an IBN, what problems would regulators face in seeking to permit the company to recover from telephone customers no more than the amounts required to cover the cost of a separate narrowband network?

DIVERSITY OF VOICES AND FIRST AMENDMENT PROTECTION

We have assumed that telephone companies are given full freedom to use their video channels in whatever ways best serve their financial interests. However, issues arise about whether telephone companies should be permitted (a) to operate only as video common carriers, (b) to program their own video channels, but only with materials procured from outside sources, and (c) to fill channels with their own programming, that is, to vertically integrate into the supply of programming as some cable operators have done.

These issues are important because of the possible effects on the diversity of information and its availability to the American public. For example, would telephone companies, if given the same freedom as cable operators to program their own channels (i.e., to be video publishers), provide a greater or lesser degree of diversity? Is the regulation of telephone companies as public utilities a factor that would affect their decisions about program choices, e.g., restrictions on channel access and content because of actual or potential pressure from government regulators? What First Amendment issues arise from answers to these questions?

These are but a few of the questions that merit further analysis. We hope that the analytic framework in this study will provide the foundation for that task.

VII. CONCLUSIONS

This study concludes that, unless the demand for switched video is strong, the abolition of the crossownership ban would not lead to competition between telephone and cable television companies in video markets nor would it improve the prospects for new services. Telephone companies will face formidable barriers in offering integrated broadband services during the 1990s. This situation arises because of (a) the high cost of switched video services in the face of a highly uncertain market, (b) competition from cable television systems that already pass more than 80 percent of the nation's households, (c) the piecemeal nature of new residential construction, and (d) the high cost of integrated facilities relative to the costs of separate narrowband and broadband networks. Although continuing technological advances will progressively reduce the costs of IBNs, these same advances will also reduce the costs of separate fiber/copper narrowband and broadband networks. It is not clear when, if ever, it will become cheaper to construct IBNs than separate networks.

As a percentage of investment, maintenance costs for an IBN may be no lower, and may be higher, than those of separate telephone and cable television facilities. The decentralization of sophisticated electronics required for an IBN could compromise the reliability of service. Additional maintenance expenses may be required to maintain the reliability of telephone service at today's high levels.

This study suggests that even if all legal restrictions were lifted, households will continue to be served separately by cable television networks and by switched narrowband networks in the foreseeable future. In some markets both networks will be owned by one entity. In others, telephone services will continue to be supplied by telephone companies and television services by cable companies. These outcomes depend in part on whether elimination of the ban encourages mergers of telephone and cable companies.

Other conclusions are:

- Unless the demand for switched video is strong, telephone company entry would likely take the form of a broadband network separate from its narrowband network instead of through construction of an IBN.
- Construction of a narrowband fiber network as a transitional step toward an IBN is not promising because of high costs.

- In large new communities with telecommunications facilities yet to be built, telephone companies may be able to move more quickly than cable operators to supply video service if asymmetries in the local franchising process handicaps cable operators, or if telephone companies are able to subsidize their entry into video from telephone revenues.
- In existing communities, incumbent cable operators have an advantage over telephone companies by being able to install fiber in their trunk lines to *immediately* improve video service, since broadband lines already exist to the home. In contrast, attempts to provide *any* video by upgrades of telephone networks would face bottlenecks, since telephone links to the home do not have broadband capability.
- In existing communities, cross-subsidization by telephone companies seeking to compete with cable operators is unlikely because the amounts of subsidization required would be large and easy for regulators to spot.
- Use of price caps for telephone service, based on the costs of a stand-alone narrowband plant, may help protect against cross-subsidization.
- Mergers between cable television and telephone companies may arise because of (a) cost savings in combining the maintenance and other functions of separate networks, and (b) the desire to foreclose potential competition between the two in nonvideo markets.
- Whether the crossownership ban should be retained or abolished depends on a weighing of factors in addition to issues of competition and development of new services addressed in this study. These factors include the effects on R&D spending by telephone companies, cost savings from merged activities, anticompetitive concentration of information sources, problems posed by cross-subsidization, and effects on program diversity and related First Amendment concerns.

In closing, we invite the reader to experiment with our analytic framework, using different assumptions and other inputs. Perhaps a plausible case can be made for lower IBN cost estimates than ours. If so, however, we would urge one note of caution: Alternatives to the IBN, such as our hybrid narrowband and broadband networks, also should be assessed in light of these same inputs. For it is the *differences* between network costs, not network costs themselves, that drive the results of our study.

Appendix A

RESIDENTIAL INTEGRATED BROADBAND NETWORKS

This appendix describes the engineering cost models used to calculate the cost of a fiber optic broadband network in the subscriber loop.[1] We consider three network architectures: active double star, passive double star, and switched star. We describe the assumptions underlying the structure and layout of the networks, and explain the basis for our cost estimates of network components.

NETWORK SERVICES AND CHANNELIZATION

Integrating diverse narrowband and broadband services on a single fiber requires a standard transmission structure. The emergence of the SONET standard provides the guidance under which different services can be combined on fiber, while leaving open decisions about the standard data rates for particular services. A key decision for residential networks is the data rate of a video signal, the value of which represents a tradeoff between the available transmission capacity and the cost of compression and desired signal quality. We assume a data rate of 155.52 Mb/s (the STS-3 rate defined in SONET) for each video signal, which is more than adequate to carry a single noncompressed NTSC-quality video channel. In addition, we anticipate that higher-quality video signals, such as HDTV, can be compressed to 155.52 Mb/s.[2]

The CCITT has yet to agree upon a standard broadband interface between the network and the subscriber, although the STS-3 and STS-12 (622.08 Mb/s) rates are seriously being considered.[3] For the switched star and active double star architectures, we assume a total data rate of STS-12 to each subscriber, equivalent to four STS-3 broadband channels.[4] For the passive double star, each subscriber

[1]For related work, see Sirbu et al. (1989).

[2]Rzeszewski (1988).

[3]Spears (1988).

[4]Alternatively, we could consider the case of an STS-3 subscriber line rate composed of three STS-1 video channels for these architectures. Our calculations suggest that any savings in capacity would be offset by increased coder/decoder (codec) costs, resulting in

receives an STS-1 signal (51.84 Mb/s) which is capable of carrying a single, compressed NTSC video channel. Thus, we assume that the following services are available:

- Two-way narrowband services (up to the N-ISDN rate of 144 Kb/s);
- Access to 64 channels of distributive video, including pay-per-view channels;
- At least one (and in most cases, four) switched video channels to each video subscriber depending upon the network architecture.

We assume the following usage patterns:

- 100 percent penetration of two-way narrowband services;
- 40, 60, and 80 percent penetration of one-way (downstream) broadband video services (includes both distributive and on-demand switched video service);
- A weekly average of 45 minutes to six hours of on-demand video viewing per household, with various assumptions concerning the peak-hour demand, and with 20 percent of the homes requesting a second channel during the peak busy hour.

NETWORK LAYOUT

The distances between the central office and subscribers are given by a distribution of residential loop lengths taken from a survey of existing Bell telephone networks.[5]

The assumed serving area encompasses a new residential development consisting of a square area of 1024 households, 32 homes on a side, laid out in a grid of square blocks with a housing density of 88 homes per street mile. The RDU is located in the center of the serving area. Cable routes in the distribution loop are part of the new serving area and follow the same square grid of streets and rights-of-way. Whenever possible, the same trench is used to carry distribution and drop cables. Installation of the feeder and distribution cable is assumed to cost $12 and $4 per meter, respectively, excluding inner duct.

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capital cost savings of only about 5 percent over our base case. Moreover, the STS-1 signal would probably be insufficient to carry HDTV signals.

[5]Bellcore (1986).

NETWORK COMPONENTS

Our cost forecasts assume widespread use of optical components in the 1995–2000 time frame. While most of the components are available off the shelf today, we allow for the maturing of technologies in some components that exist only in prototype form. Our 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 chip sets, which leads to large reductions below today's costs. Table A.1 lists our estimates of the current and future costs of network components based on published sources, noted below, and contacts with manufacturers. As shown in Table A.3 below, the cost of electronic devices is marked up by 40 percent to cover the costs of site engineering, field installation, and acceptance testing.[6]

Along with considering technologies and architectures likely to be used in residential fiber networks, we discard those technologies that seem too distant technologically to be considered within the time frame of our analysis. Coherent modulation and detection methods, and photonic switching, fall into this category.[7]

Passive Components

Passive components of a fiber optic network operate without electrical power. Optical fiber, connectors, splices, couplers, and wavelength division multiplexers (WDM) are examples.[8] We assume that all cables are installed underground.

The current price of single mode fiber is in the neighborhood of $0.20 per meter, and some have forecast price reductions to as low as $0.04 per meter by 1992.[9] We assume that fiber will be available at $0.10 per meter along with a cost of $2 per meter for the cable sheath in the feeder loop (a cost of $0.14 per fiber per meter for a 50-fiber cable) and $1 per meter for the sheath in the distribution loop ($0.15 per fiber per meter in the switched star and active double star, $0.30 per fiber per meter in the passive double star).[10] A protection factor of

[6]The magnitude of the markup probably varies between 20 percent to 80 percent depending upon local conditions and the nature of the equipment. See Lu and Wolff (1988).

[7]Wagner et al. (1987).

[8]For a review of advances in passive component technologies see Keck et al. (1989).

[9]Linnel and Bussey (1988).

[10]One study assumes feeder fiber cable cost of $0.13 to $0.23 per fiber per meter, and distribution fiber between $0.50 and $0.66 per fiber per meter. See Wagner and Lemberg (1989).

Table A.1

ESTIMATED COSTS OF NETWORK COMPONENTS
(In dollars)

Component	Current Cost	Future Cost	Description
Single mode fiber (per meter)	0.20	0.10	Glass fiber
Feeder fiber sheath (per meter)	NA	2.0	Feeder fiber cable
Distribution fiber sheath (per meter)	NA	1.0	Distribution loop fiber cable
Feeder inner duct (per meter)	1.15	1.15	Protective duct, not including installation
Distribution inner duct (per meter)	0.75	0.75	Protective duct, not including installation
STS-12 optical transmitter	750	60	Light emitting or laser diode, circuitry, packaging
STS-48 optical transmitter	2500	200	Laser diode, circuitry, packaging
STS-12 optical receiver	300	40	PIN photodiode
STS-48 optical receiver	1500	120	Avalanche or PIN photodiode
Connector	75	25	Single mode, includes installation
Splice	40	15	Cost per splice including labor
Wavelength division multiplexer	100	35	Coarse wavelength division multiplexing
Switching card	NA	200	64x64 video switching card
Broadband multiplexer	NA	2240	Multiplexing 16 STS-3 channels
Star coupler	80	25	Cost per port of star coupler
Video codec	NA	80	STS-3 rate digital/analog converter
Controlled environment vault	60,000	60,000	24 ft controlled environment vault

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

200 percent in the feeder and 25 percent in the distribution loop specifies the percentage of dark fiber installed to cover fiber failures and future growth.

We assume use of single mode fiber throughout the subscriber loop plant. Installation of feeder and distribution cable includes inner duct. Drop cables are without inner duct but have a rodent-proof sheath costing $0.85 per meter.

With respect to the choice between using connectors or using splices to interconnect fibers in the field, the former is currently more than twice as costly as field splicing and this differential may widen.[11] Moreover, the trend appears to be away from single fiber connections

[11]Keck (1989).

toward multifiber designs in conjunction with ribbon fibers.[12] Our models assume that low-loss, multifiber fusion splices are used to connect feeder cables (each carrying 50 fibers), while higher-loss mechanical splices are used for the drop to the home. We estimate the cost of both splicing methods, including installation, at $15 per splice. In the feeder loop, additional splices are dictated by the 3000 foot (915 meter) manufactured distance of the fiber. To assure adequate flexibility, we assume that connectors are used to attach the fiber to network equipment at the central office, RDU, and the subscriber's premises.

In the distribution loop, smaller cables radiate from the RDU to eliminate the need for splicing beyond the RDU. A standard cable size of five fibers is assumed in the passive double star architecture, while a size of 20 fibers is assumed in the switched star and active double star architectures. Splices are needed to connect the distribution cables to the drop cables, which run from manholes (spaced one or two per block) to each residence.

Inclusion of electronic equipment at the RDU requires the installation of controlled environment vaults (CEVs) for protection from the natural elements. The total cost of a 24 square foot CEV is $60,000.[13] In the passive double star, the RDU houses star couplers (without the need for CEVs), which we estimate to cost $25 per port.[14] Also, a choice exists between running two fibers to every subscriber, one for each direction, or using a single fiber along with a WDM. The current cost of a WDM is about $150. However, in volume production, manufacturers project a cost of $35 per WDM component.[15] At this cost, our analysis suggests that it will be cheaper to use a WDM throughout the distribution loop.

Electronic Components

The optical power budget determines the combination of optical sources and detectors to be used in any given configuration. Either light emitting diodes (LEDs) or laser diodes (LDs) are likely to be used as the optical sources. LEDs are cheaper and more reliable than LDs, but may have insufficient optical output power for the bit rates and loop distances involved.[16] Avalanche photodiodes (APDs) improve the power sensitivity of the optical receiver relative to PIN photodiodes but

[12]Haag et al. (1989).

[13]Moondra (1989).

[14]Andersson (1988).

[15]Baskerville (1989).

[16]Spears (1988) and Tsuchiya et al. (1989).

are more expensive and more sensitive to temperature variations. Consequently, LEDs are chosen over laser diodes, just as PIN photodiodes are chosen over APDs whenever the optical power levels make the exchange possible. Including the costs of materials, signal processing, packaging, and testing, we assume a cost of $100 for a transmitter/receiver pair at the STS-12 rate and $320 at the STS-48 rate.[17]

The transfer modes of a network define the switching and multiplexing techniques of the system. We assume a synchronous transfer mode approach using circuit switching and time division multiplexing (TDM). Video signals are directed with a space division switch with VLSI CMOS crosspoints operating at the STS-3 rate. For narrowband signals we assume the use of the existing switch at the central office and, when necessary, simple demultiplexing at the RDU. Such a circuit-switched approach has been demonstrated by several research groups.[18] Thus, it appears that relatively inexpensive switching components for STS-3 digital video channels can be realized using VLSI circuitry. We assume that a 64x64 video channel switching card costs $200.

Even with the continued use of existing N-ISDN switches, more needs to be factored into the costs of a broadband switching than just the price of the switching hardware. Development of the software needed to operate the equipment is costly, accounting for as much as 70 percent of the total development costs of a switch.[19] We assume a fixed cost of $100 per home to cover these costs throughout the network.

Multiplexing is another key electronic technology. For combining and dividing video signals below the STS-12 rate, we expect inexpensive VLSI multiplexing devices to be developed. The active double star architecture calls for multiplexing multiple video channels up to a feeder rate of STS-48. However, this rate exceeds the capabilities of CMOS technology and requires gallium arsenide components of only medium-scale integration. Consequently, we estimate that these multiplexers will cost $2240 ($140 per STS-3 channel on each side), which is more than that for switching components. The total cost of the residential fiber network is highly sensitive to the cost of broadband

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[17]Dawson (1988).

[18]See Schaffer (1986) and Cooperman et al. (1989).

[19]The average cost per line in 1987 for a metropolitan area central office switch was about $200. See Moondra (1989).

multiplexers, with a strong dependence upon the subscriber demand for switched video channels.[20]

In addition to the synchronous transfer mode discussed above, another approach receiving considerable attention in the literature is the Asynchronous Transfer Mode (ATM). ATM techniques use a packet-switching fabric for switching and multiplexing that could allow services, independent of their bandwidth, to be carried over an integrated high-speed switching fabric.[21] Although ATM techniques are consistent with the star and double star network architectures examined here, we do not consider explicitly the economics of this approach.[22] However, our study does provide a benchmark against which the costs of ATM components can be compared. If the inherent flexibility of ATM allows more services to be transported, its higher electronics costs might be justified.

Because most homes will still have a standard analog television set during the 1990s, a video codec is required to convert the digital video signal to the standard NTSC analog format. Codecs involving four custom chips plus additional circuitry have been demonstrated.[23] We assume a cost of $80 for the codec, and an additional $40 for the video coder to decompress an STS-1 signal.

Our cost estimates for the three architectures are shown in Tables A.2, A.4, and A.5.

To demonstrate how we obtain the total cost per home passed from the numerous estimates of costs for network components in Table A.2, we show in Table A.3 the derivation for one case taken from Table A.2—the case of 1.5 hours per week of on-demand viewing. The other cases in Tables A.2, A.4, and A.5 are derived in similar fashion.

Subscriber Premises

Table A.6 lists the components required to serve individual residences, including customer premises equipment (CPE), using the three broadband architectures discussed above, for all-fiber narrowband

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[20]The current cost of STS-3 rate multiplexers can easily exceed tens of thousands of dollars. But these costs may decline rapidly, as we assume in our estimates. As evidence of potential cost reductions, galium arsenide chips manufactured in large quantities may cost less than $100 (without the attendant circuitry that would be required for field deployment). Such chips can multiplex eight STS-3 rate signals up to 1.2 Gb/s.

[21]Minzer and Spears (1989).

[22]Because upstream connections with the passive double star are multiplexed together at the star coupler, using time division multiplexing systems with fixed time slots, it is not clear how well ATM would work in such a system.

[23]See Andrich et al. (1987).

Table A.2

INVESTMENT COST PER HOME PASSED, ACTIVE DOUBLE STAR ARCHITECTURE, 60 PERCENT VIDEO PENETRATION
(In dollars)

Component	Single Item Cost	Hours of On-Demand Video per Week per Subscriber			
		0.75	1.5	3	6
Central Office Equipment					
Video switching,[a] control[b]	200/card, 100/home	101	101	101	101
Broadband multiplexer,[a] optical transmitter[a]	2240, 200	30	40	53	64
Voice multiplexer,[a] optical transmitter,[a] optical receiver[a]	1000, 60, 40	1	1	1	1
Power[b]	10/watt	2	2	2	2
Total		134	144	157	168
Feeder Loop					
Single mode fiber	0.10/meter	15	15	15	30
Sheath	2/meter	6	6	6	12
Cable installation	12/meter	36	36	36	36
Inner duct	1.15/meter	3	3	3	3
Splice, connector	15, 25	4	4	5	8
Total		64	64	65	89
Remote Distribution Unit					
Broadband multiplexer,[a] detector[a]	2240, 120	28	38	51	60
Remote video switching[a]	200/card	11	11	11	11
SLIC (4 subs/card),[a] WDM[a]	585/card, 35	235	235	235	235
Voice demultiplexer,[a] optical transmitter,[a] optical receiver[a]	75/home, 60, 40	105	105	105	105
Power[b]	15/watt	75	75	75	75
Controlled environment vault	60,000	59	59	59	59
Total		513	523	536	545
Distribution Loop					
Single mode fiber	0.10/meter	80	80	80	80
Sheath	1/meter	40	40	40	40
Cable installation	4/meter	39	39	39	39
Inner duct	0.75/meter	7	7	7	7
Connector	25	25	25	25	25
Pedestal/manhole terminal	100	13	13	13	13
Total		204	204	204	204
Drop Loop					
SM fiber, sheath	0.10/meter, 0.85/meter	58	58	58	58
Cable installation (buried)	1/meter	24	24	24	24
Splice, connector	15, 25	40	40	40	40
Total		122	122	122	122

Table A.2 (Continued)

Component	Single Item Cost	Hours of On-Demand Video per Week per Subscriber 0.75	1.5	3	6
		Subscriber Premises			
CPE (voice only)[b]	167	167	167	167	167
CPE (video upgrade for 60%)[b]	131	79	79	79	79
Hookup and installation[b]	50/home	50	50	50	50
Video subscription[b] (for 60%)	50/home	30	30	30	30
Power[b]	50/watt	300	300	300	300
Total		626	626	626	626
		Totals			
Total electronics		1214	1234	1260	1281
Total nonelectronics		449	449	450	473
Total network		1663	1683	1710	1754
Headend and jukebox (all electronic), see Appendix C		62	77	95	106
Overall total		**1725**	**1760**	**1805**	**1860**

[a]Electronic component, marked up 40 percent over per item cost to cover field engineering, installation, and testing.

[b]Electronic component, per item cost includes installation and testing.

service. All of our models include the equipment necessary to provide analog phone service equivalent to today's level.

All models include the cost of installation and hookup. These items include (a) installation of network equipment—including electronics at the central office, RDUs, and equipment cabinets close to or attached to houses, (b) administration, involving modifying the network software, e.g., for addition of video subscriptions, and (c) testing of new service. We assume this cost to be $100 per home with video service—$50 each for receiving narrowband and broadband services—or about two hours of labor at a burdened wage rate of $50 per hour. Installation cost in the copper scenario is $50 per copper wire pair.

The Star and Active Double Star Architectures. In both cases, the input signal feeds into the CPE at the broadband STS-12 rate. This arrangement provides enough bandwidth for four noncompressed NTSC video channels, or some number (less than or equal to four) of HDTV channels, in addition to N-ISDN capability. For the star and active double star architectures, the total cost per video subscriber is $298, shown in Table A.6.

Passive Double Star Architecture. This alternative calls for an input signal rate of STS-1 into the CPE, which provides only enough bandwidth for one compressed NTSC video channel and voice services (N-ISDN compatible). It has yet to be demonstrated that HDTV could be adequately compressed to this rate. The cost of the CPE per video subscriber is $351, shown in Table A.6.

Table A.3

COST ANALYSIS OF THE ACTIVE DOUBLE STAR ARCHITECTURE, 1.5 HOURS ON-DEMAND VIEWING PER WEEK, 60 PERCENT VIDEO PENETRATION
(In dollars)

Network Component	Single Item Cost	Total Cost per Home Passed	Description and Derivation of Total Cost
Central Office Equipment			
Video switching,[a] and control[b]	200/card, 100/home	101	3 switch cards plus $100 per subscriber for common control of switching function [1.4(3)(200) + 100(1024)] ÷ 1024
Broadband multiplexer,[a] optical transmitter[a]	2240, 100	40	12 multiplexers and transmitter packages connected to 12 active feeder fibers 12(2240 + 200)(1.4) ÷ 1024
Voice multiplexer,[a] optical transmitter,[a] optical receiver[a]	1000, 50, 50	1	One voice card per RDU 1.4(1000 + 50 + 50) ÷ 1024
Power (central office only)[b]	10/watt	2	(0.2)(10)
Total		140	
Feeder Loop			
Single mode fiber	0.10/meter	15	One 50 fiber feeder cable, 3072 meters 0.1(50)(3072) ÷ 1024
Cable sheath	2/meter	6	One 50 fiber cable sheath, 3072 meters 2(3072) ÷ 1024
Cable installation	12/meter	36	Mean feeder length of 3072 meters 12(3072) ÷ 1024
Inner duct	1.15/meter	3	Mean feeder length of 3072 meters 1.15(3072) ÷ 1024
Splice, connector	15, 25	4	Each fiber spliced 3 times, 2 connectors per active cable [3(50)(15) + 36(2)(25)] ÷ 1024
Total		64	
Remote Distribution Unit			
Broadband multiplexer,[a] detector[a]	2240, 120	38	12 multiplexers and detector packages connected to 12 active feeder fibers 12(2240 + 120)(1.4) ÷ 1024
Remote video switching[a]	200/card	11	39 switch cards to provide 4 channels per video subscriber 39(200)(1.4) ÷ 1024
SLIC (4 subs/card)[a] and WDM[a]	112.5/broadband upgrade card, 462.5/narrowband card, 35 WDM	235	256 narrowband SLICs, 154 broadband SLICs plus one WDM per home 1.4[(462.5)(256) + (112.5)(154) + (35)(1024)] ÷ 1024

Table A.3 (Continued)

Network Component	Single Item Cost	Total Cost per Home Passed	Description and Derivation of Total Cost
Voice multiplexer,[a] optical transmitter,[a] optical receiver[a]	75, 60, 40	105	One transmitter/detector pair for voice service, multiplexing per subscriber 1.4(75) + [1.4(60 + 40)] ÷ 1024
Power (RDU only)[b]	15/watt	74	Backup power, power processing plant at the RDU, 4 watts per home
Controlled environment vault	60,000	59	Large vault or hut 60,000 ÷ 1024
Total		523	
	Distribution Loop		
Single mode fiber	0.10/meter	80	Average of 800 meters of dedicated fiber plant (incl. protection) per home
Cable sheath	1/meter	40	40 meters of dedicated fiber sheath per home
Cable installation	4/meter	39	10 meters common trenching per home
Inner duct (per meter)	0.75	7	Average of 10 meters common duct per home
Connector	25	25	One connector per home
Pedestal/manhole terminal	100	13	128 terminals for 1024 homes
Total		204	
	Drop Loop		
Fiber, sheath (per meter)	0.10, 0.85	58	55 meters of drop fiber (2) and rodent proof sheath 2(55)(0.1) + (55)(0.85)
Cable installation (buried)	1/meter	24	24 meters common/dedicated trench
Splice, connector	15, 25	40	Single splice point per home, connector to CPE
Total		122	
	Subscriber Premises		
CPE (voice only)[b]	167	167	See Table A.6
CPE (video upgrade)[b]	131	79	60% of the homes upgraded 0.6(131)
Hookup and installation[b]	50/home	50	Activating CPE and network software
Video subscription (60%)[b]	50/home	30	Modified CO, RDU, CPE electronics for video hookup 0.6(50)
Power[b]	50/watt	300	ONI power processing, 8-hour battery backup, AC power outlet (50)(6 watts)
Total		626	
Overall total		**1683**	

[a]Electronic component marked up 40 percent over per item cost for field engineering, installation, and testing.

[b]Electronic component, includes installation and testing in per item cost.

Table A.4

INVESTMENT COST OF PASSIVE DOUBLE STAR ARCHITECTURE PER HOME PASSED, 60 PERCENT VIDEO PENETRATION
(In dollars)

Network Component	Single Item Cost	Cost of Fiber per Meter		
		0.05	0.10	0.20
Central Office Equipment				
Video switching,[a] control[b]	200/card, 100/home	105	105	105
Broadband multiplexer,[a] optical transmitter[a]	1180, 200	164	164	164
Voice optical receiver,[a] WDM[a]	55, 35	11	11	11
Power[b]	10/watt	10	10	10
Total		290	290	290
Feeder Loop				
Single mode fiber	0.10/meter	52	105	209
Cable sheath	2/meter	42	42	42
Cable installation	12/meter	36	36	36
Inner duct	1.15/meter	3	3	3
Splice, connector	15, 25	28	28	28
Total		161	214	318
Distribution Loop				
Single mode fiber	various	7	14	28
Cable sheath	1/meter	28	28	28
Cable installation	4/meter	39	39	39
Inner duct, splice	0.75/meter, 15	9	9	9
Fiber splitter, terminal	25/port, 100	34	34	34
Total		117	124	138
Drop Loop				
Fiber, sheath (per meter)	0.10, 0.85	57	63	76
Cable installation (buried)	1/meter	24	24	24
Connectors	25	50	50	50
Total		131	137	150
Subscriber Premises				
CPE (voice only)[b]	182	182	182	182
CPE (video upgrade for 60%)[b]	169	101	101	101
Hookup and installation[b]	50/home	50	50	50
Video subscription (for 60%)[b]	50/home	30	30	30
AC power outlet,[b] battery backup[b]	50/watt	300	300	300
Total		663	663	663
Overall total		**1362**	**1428**	**1559**

[a]Electronic component, marked up 40 percent over per item cost to cover field engineering, installation, and testing.

[b]Electronic component, per item cost includes installation and testing.

Table A.5

INVESTMENT COST OF SWTTCHED STAR ARCHITECTURE PER HOME PASSED, 60 PERCENT VIDEO PENETRATION
(In dollars)

Network Component	Single Item Cost	Cost of Fiber per Meter		
		0.05	0.10	0.20
Central Office Equipment				
Video switching,[a] control[b]	200/card, 100/home	103	103	103
Line interface card (voice),[a] WDM[a]	462.5 per 4 sub, 35	211	211	211
Video electronics upgrade[a]	112.5 per 4 sub	24	24	24
Power (per watt)[b]	10	40	40	40
Total		378	378	378
Feeder Loop				
Single mode fiber	Variable	193	388	778
Cable sheath	2/meter	156	156	156
Cable installation	12/meter	36	36	36
Inner duct	1.15/meter	3	3	3
Splice, connector	15, 25	101	101	101
Total		489	684	1074
Distribution Loop				
Single mode fiber	0.10/meter	40	80	160
Cable sheath	1/meter	40	40	40
Cable installation	4/meter	39	39	39
Inner duct	0.75/meter	7	7	7
Terminal	100	13	13	13
Total		139	179	259
Drop Loop				
SM fiber, sheath (per meter)	Variable, 0.85	52	58	68
Cable installation (buried)	1/meter	24	24	24
Splice, connector	15, 25	40	40	40
Total		116	122	132
Subscriber Premises				
CPE (voice only)[b]	167	167	167	167
CPE (video upgrade for 60%)[b]	131	79	79	79
Hookup and installation[b]	50/home	50	50	50
Video subscription (for 60%)[b]	50/home	30	30	30
AC power outlet,[b] battery backup[b]	50/watt	300	300	300
Total		626	626	626
Overall total		**1748**	**1989**	**2469**

[b]Electronic component, marked up 40 percent over single item cost to cover field engineering, installation, and testing.

[b]Electronic component, single item cost includes installation and testing.

Table A.6

COST OF CUSTOMER PREMISES EQUIPMENT PER HOME PASSED,
60 PERCENT VIDEO PENETRATION
(In dollars)

Item	Star and Active Double Star	Passive Double Star	Narrowband Only over Fiber	Comments
		Narrowband Components		
Optical transmitter	60	60	60	LED
Optical receiver	40	40	40	PIN photodiode
ISDN chip	15	15	15	Includes battery, overvoltage, protection, ringing, signaling, hybrid, and testing functions
Ranging protocol chip		15		Timing of upstream voice signal
D-A converter	7	7	7	Digital-to-analog converter
WDM	35	35	35	Wavelength division multiplexer
Cabinet	10	10	10	Installed outside of premises
		Broadband Components		
Multiplexer	35	25		(De)mulitplexing 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 percent of subscribers request second video channel requiring another video codec and coder (if necessary)
Total	298	351	167	

Voice Only over Fiber. The voice-only model in Appendix D below assumes the double star architecture, using the same equipment except for the video equipment. The cost of the CPE per home passed is $167, shown in Table A.6. In contrast, using copper in the drop loop would eliminate the need to convert the optical signal to an electrical signal (or vice versa) in the CPE. The only cost components necessary are the installation fees (at $80/line) and the cost of a grounded lightning protection block (one per line at $30 each).

Appendix B

SENSITIVITY OF INVESTMENT COST OF ACTIVE DOUBLE STAR ARCHITECTURE TO PEAK-HOUR LOADS

We examine the sensitivity of total average costs per subscriber to the peak hourly viewing share of on-demand video service under three different scenarios.

1. The low scenario involves viewing shares of 0.0375, 0.075, 0.12, and 0.15 for the range of average hourly viewing of 0.75, 1.5, 3, and 6 hours, respectively.
2. The base case involves viewing shares of 0.075, 0.15, 0.24, and 0.3 for the range of average hourly viewing of 0.75, 1.5, 3, and 6 hours, respectively.
3. The high scenario involves viewing shares of 0.15, 0.3, 0.45, and 0.48 for the range of average hourly viewing of 0.75, 1.5, 3, and 6 hours, respectively.

All cost estimates, shown in Table B.1, are for the cost per home passed for the active double star architecture at a $0.10 per meter cost of fiber and a 60 percent penetration rate of video services. The figures include costs of the headend and video jukebox.

Table B.1

EFFECTS OF ALTERNATIVE VIEWING PATTERNS ON INVESTMENT COST PER HOME PASSED
(In dollars)

	Hours of On-Demand Video per Week per Subscriber			
Peak Load	0.75	1.5	3	6
Low	1703	1725	1747	1760
Base case	1725	1760	1805	1860
High	1760	1860	1930	1942

Appendix C

BROADBAND HEADEND AND VIDEO JUKEBOX COSTS

This appendix reports our estimates of costs for a broadband video headend equipped with a video jukebox for switched broadband services. The costs are assumed to be shared over all 25,600 households located within the central office (CO) serving area. The model assumes that the headend is close to the CO; we do not include any costs for transporting video signals between the headend and the CO. Thus, the first stage of video switching occurs at the CO—consistent with our models in Appendix A.

HEADEND COSTS

Table C.1 lists the costs of headend equipment required to provide distributed video service under the assumption that the network uses a

Table C.1

INVESTMENT COST OF HEADEND EQUIPMENT, 60 PERCENT VIDEO PENETRATION
(In dollars)

Component	Single Item Cost	Total Cost	Cost Calculations
Tower and building	35,000	35,000	
Earth station and over-the-air antenna	30,000	30,000	
Microwave antenna	15,000	15,000	
FM receivers	5,000	5,000	
Standby power	9,000	9,000	
Microwave receiver	4,500/channel	144,000	32 channels received by microwave or satellite dish (32)(4,500)
Codec	80/channel	5,120	For all 64 channels (64)(80)
Total		243,100	
Total per video subscriber		16	243,100 ÷ [(25,600)(0.6)]

SOURCE: Webb (1983).

digital transmission format. The total cost is $243,100 for a 64 channel cable system, equal to $16 per video subscriber at 60 percent penetration, or $10 per home passed. In comparison, today's analog transmission systems cost about $1875 per channel for signal processing and modulators, which would replace the codec in Table C.1 required for digital transmission. The total cost of the analog system headend would be $358,000 for a 64 channel cable system, or $23 per video subscriber, which is comparable to estimates from other sources.[1] The digital headend appears cheaper than its analog counterpart because we have not included multiplexing and transmitter component costs in the total. These are included in the central office.

ON-DEMAND VIDEO EQUIPMENT

Video Jukebox

A true on-demand video service requires that the customer's request for a specific program be promptly satisfied. Thus, the requested program must be retrieved from a video library and loaded into a video disk or cassette player. Many technology options are possible. For example, the video loader could be a robotic device that automatically accesses or loads the appropriate program into the player upon electronic request (i.e., using touchtone telephones), or an employee could manually perform the same tasks. Automated jukeboxes are not without precedent.[2] Accordingly, we assume a jukebox capable of accessing over 6000 programs at a cost of $800,000.

Video storage and access methods are key technologies of the video jukebox. Today, analog storage technology and video players are much cheaper than their digital counterparts. As a result, analog video tapes and VCRs are the current standard of choice, benefitting both from high-volume sales and a mature technology. One drawback, however, is that a separate playing mechanism and tape are required for each viewing. Random access digital technology, in contrast, would allow several simultaneous viewings of the same video using one copy.

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[1]Webb (1983) calculates a cost near $395,000 under similar assumptions. Shooshan & Jackson (1987a, p. 13) estimate a lower figure of $200,000 for 35,000 subscribers. However, this figure may be for a lower-capacity system.

[2]Storage Technology Corporation markets a $500,000 (nonvideo) tape cartridge loader that can sort and load 6000 stored cartridges onto eight tape units in 11 seconds. DEC has developed an optical disk jukebox that holds 64 12-inch disks at a cost of $205,000. *Electronic Business,* September 1, 1988, p. 20. See also Smalley (1989).

Thus, even though the multiple access capability of a digital player is technically more efficient than the videotape alternative, it appears unlikely that such a digital recorder system will be economic within the next decade—the time frame of our study.[3] The problem with current digital storage technology is that its maximum access rate is limited to 20 Mb/s, much too low for entertainment video applications unless costly signal compression is applied. Consequently, most digital video alternatives being developed apply compression techniques that result in video signal rates much lower than those we have assumed, based on the SONET signal hierarchy. For example, one alternative that might be eventually favored is the digital video interactive (DV-1) technology currently being introduced in educational software and process analysis video applications. DV-1 stores 70 minutes of highly compressed full motion video using a CD-ROM disk, which in turn is decompressed and displayed in real time.[4]

Eventually, we may see widespread digital video applications with highly compressed video. If video signals were compressed down to 10 Mb/s or less, subscriber line rates greater than 50 Mb/s (compared with the 600 Mb/s we have assumed) would be adequate for residential applications. A primary economic barrier to such applications is the additional cost of equipment needed at customers' premises to decompress video signals.[5] Signal compression would be facilitated with the deployment of ATM components that provide a platform to deliver nonuniform data rates—such as video signals compressed to a rate below about 20 Mb/s as dictated by the amount of movement in the video image. Again, however, such technological developments are unlikely to be available within the next decade for the uses described in this study.

Thus, for lack of any other viable alternative, we assume that a video jukebox using videotapes and VCRs (with automated operation) is the most likely approach. The demand for switched video services determines the number of video players required in the headend. We estimate that the number of VCRs, costing $200 apiece, corresponds to the peak hour viewing demands as determined by the level of penetration and our demand model discussed in the report.

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[3]Professor Mark Kryder, private conversation, Carnegie Mellon University, December, 1989.

[4]See Isaac (1989).

[5]Video compression is a costly process requiring extensive computer processing capabilities. However, because the process must be repeated only once and copies of compressed video distributed thereafter, the costs of compression can be distributed widely over uses to reduce unit costs.

Video Library

Switched broadband services require a library to supply a variety of programming to the subscriber. Uncertainty concerning subscriber viewing habits makes it difficult to estimate the number of video copies needed in inventory.[6] For example, are the current patterns of video rentals for VCR viewing indicative of viewer preferences? Or are they influenced by subscribers who have to settle for second or third choices, when their first choice has already been rented?

We assume that the video library has 5000 titles available in inventory—equivalent to that of a current large video cassette rental outlet. Because it is necessary to hold multiple copies of frequently requested programs—today's video outlets might hold as many as 100 copies of a popular video—the number of cassettes in the library is given by the demand for switched video service adjusted to reflect a 30 percent overhead in titles. In addition, we assume that at any given time 1 percent of the titles have 100 copies and that 75 percent of the titles have at least one backup copy. Given these assumptions, we calculate that between 14,110 and 25,550 programs would be held in the video library, depending on the video penetration level, and peak demand patterns. We estimate a cost of $5 per copy, exclusive of royalty payments to program suppliers.

Video Codec

Because we assume that analog video players must be used, video codecs are necessary for each output channel in the video jukebox to convert the analog video signal to digital format. Both the distributed video channels and switched video channels require codecs that convert the signal into a format ready for transport at the SONET STS-3 rate at a cost of $80 per channel.[7]

The total cost of the jukebox and associated equipment is shown in Table C.2. The total cost per video subscriber of $118 plus the $23 from Table C.1 gives a total of $141 shown in Table C.3.

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[6]The jukebox technology dictates the size of the inventory as well. A CD-ROM jukebox that provides simultaneous random access to several subscribers might drastically reduce the number of copies necessary in the library, although the amount of CD-ROM required may be unrealistic. At 45 Mb/s a two-hour video would require a massive 40.5 Gigabytes of storage. If compression to 10 Mb/s is possible, then the same video would occupy 9 Gigabytes of storage. As a base for comparison, Eastman-Kodak uses 14-inch, double-sided disks with a total storage capacity of 6.8 Gigabytes in its optical disk jukebox. See Goff and Greenstein (1988).

[7]Estimate is based upon a four-chip implementation of a video codec. See Andrich et al. (1987).

Table C.2

INVESTMENT COST OF ON-DEMAND VIDEO EQUIPMENT,
1.5 HOURS ON-DEMAND VIEWING PER WEEK,
60 PERCENT VIDEO PENETRATION
(In dollars)

Component	Item Cost	Total Cost	Description
Video jukebox	800,000	800,000	
Video library	5/cassette	88,250	17,650 cassettes
Video player	200/player	600,000	3,000 players
Codec	80/channel	240,000	3,000 codecs
Total		1,728,250	
Total per video subscriber		112	

TOTAL HEADEND AND JUKEBOX COSTS

Table C.3 shows total costs with and without the video jukebox. The figures depend on the assumed penetration rate of the video services and the average offered traffic per subscriber for switched video services.

Table C.3

INVESTMENT COST OF VIDEO HEADEND
AND JUKEBOX
(In dollars)

% On-Demand Video Penetration	Hours of On-Demand Video per Week per Subscriber			
	0.75	1.5	3	6
Without Video Jukebox				
40	24	24	24	24
60	16	16	16	16
80	12	12	12	12
With Video Jukebox				
40	74	87	102	112
60	87	112	142	161
80	112	161	210	219

NOTE: All these costs are considered as electronic in computation of annualized figures.

Appendix D

AN IBN WITHOUT SWITCHED VIDEO

This appendix describes our estimates of the costs of providing narrowband and nonswitched or distributive video on an optical broadband network. The figures are obtained by modifying the active double star architecture to carry switched narrowband services and distributed video service (eliminating the switched video service).

An important caveat applies to our use of the active double star architecture in this application. In fact, there may be more appropriate architectures, based on analog video transmission techniques, to carry distributed video service.[1] For the three architectures examined in the study, however, the active double star is the best alternative. With only 12 channels per shared fiber (not enough to deliver the full range of video channels available today), the passive double star architecture would require broadband switching capability to deliver the distributed video channels.

Table D.1 shows the investment cost savings obtained by deleting switched video capability from the active double star network that would otherwise carry 1.5 hours per week on-demand video per video subscriber. Savings at the central office, feeder loop, and RDU amount to $261 per home passed, with a 60 percent video penetration level. The costs of the distribution loop, drop loop, and subscriber premises equipment are unaffected, except the customer premises equipment consumes one less watt of power resulting in a saving of $50.

[1]Olshansky (1988).

Table D.1

INVESTMENT COST SAVINGS PER HOME PASSED FROM DELETION OF SWITCHED VIDEO IN THE ACTIVE DOUBLE STAR NETWORK BASE CASE
(In dollars)

	With Switched Video	Without Switched Video
Headend Equipment		
Distributed video equipment	9	9
Video jukebox	68	
Total	77	9
Central Office Equipment		
Video switching and control	101	20
Broadband multiplexer, optical transmitter	40	13
Voice multiplexer, optical transmitter, optical receiver	1	1
Power	2	1
Total	144	35
Feeder Loop		
Single mode fiber	15	3
Cable sheath	6	6
Underground cable installation	36	36
Inner duct	3	3
Fiber splicing and connector	4	1
Total	64	49
Remote Distribution Unit		
Broadband multiplexer, detector	38	13
Remote video switching	11	5
SLIC (4 subs/card) and WDM	235	212
Voice multiplexer, optical transmitter, optical receiver	105	105
Power	75	60
Controlled environment vault	59	59
Total	523	454
Totals		
Total distribution, drop loop, CPE	952	902
Total electronics	1311	1015
Total nonelectronics	449	434
Overall total	**1760**	**1449**

Appendix E

COPPER/FIBER NARROWBAND NETWORK

We consider the current cost of a digital loop carrier system and compare it to the projected future costs of our broadband models. In the feeder portion of the network, single mode fiber is placed at multiples of the DS3 rate (45 Mb/s) to carry multiplexed voice circuits from the CO to the RDU in a logical star design. A demultiplexer reduces the DS3 signal at the RDU into DS1 signals (1.5 Mb/s) that feed into several subscriber line interface channel banks to distribute the voice signals to the appropriate copper wire pair at the DS0 rate (64 Kb/s). Copper pairs run from the RDU to a terminal housing, one for every eight households, and then a drop wire runs to the residence. All construction is assumed to be underground.

Two different sets of figures are reported: one representing current estimates of the network costs and a second representing estimates of the component costs some 5 to 10 years in the future (the numbers used in our fiber model). As before, electronic components are marked up 40 percent for installation, and all cable is installed underground.

CENTRAL OFFICE

As in the fiber models, costing of the network begins just below the central office switch down to the subscriber premises. No costs are assigned for the central office switch (unless it is a necessary addition to the architecture under examination, e.g., a broadband fiber network requiring a video switch at the central office). The multiplexer is assumed to handle up to 90 Mb/s (two DS3 signals).

FEEDER LOOP

The feeder loop consists of single mode fiber buried in new conduit. The model assumes a feeder cable size of 10, providing a 1:5 protection factor (only two fibers are used initially). The mean length of the feeder loop is 3072 meters.

Table E.1

ESTIMATED COSTS OF A DIGITAL LOOP CARRIER
(In dollars)

	Current Cost	Future Cost	Cost per Home Passed	
			Current	Future
Central Office Equipment				
Optical source,[a] optical receiver[a]	750, 300	60, 40	1	1
Multiplexer[a]	11,000	1000	15	1
Power[b]	10/watt	10/watt	1	1
Total			17	3
Feeder Loop				
Single mode fiber	0.20/meter	0.10/meter	5	2
Cable sheath	1/meter	2.0/meter	3	3
Cable installation	12/meter	12/meter	36	36
Inner duct	1.15/meter	1.15/meter	3	3
Splice, connector	40, 75	15, 25	2	1
Total			49	45
Remote Distribution Unit				
Optical source, optical receiver[a]	750, 300	60, 40	1	1
Multiplexer[a]	11,000	1000	15	1
Line interface unit[a]	193,600	83,600	265	114
Subscriber line card (20% second drops)[a]	67	28	89	37
Power[b]	15/watt	15/watt	36	36
Controlled environment vault	60,000	60,000	59	59
Total			465	248
Distribution Loop				
Copper pairs and cable	Variable	Variable	29	29
Cable installation	4/meter	4/meter	42	42
Inner duct	0.75/meter	0.75/meter	7	7
Splices	1.67/splice	1.67/splice	2	2
Pedestal/manhole terminal	50	50	6	6
Total			86	86
Drop Loop				
Drop cable	0.50	0.50	28	28
Cable installation (buried)	1/meter	1/meter	24	24
Splice, connector	1.67/splice	1.67/splice	2	2
Total			54	54
Subscriber Premises (incl. second drop)				
Protective block	30	30	36	36
Hookup and installation[b]	80/home	80/home	96	96
Total			132	132
Totals				
Total electronics			519	287
Total nonelectronics			284	281
Overall total			**803**	**568**

[a]Electronic component marked up 40 percent over per item cost to cover field engineering, installation, and testing.

[b]Electronic component per item cost includes installation and testing.

REMOTE DISTRIBUTION UNIT

At the RDU, the DS3 signals are demultiplexed with the same type of equipment found at the central office. The signal is further demultiplexed and directed to the correct copper wire pair by line interface units. The first unit acts as a first-stage switch and directs the signals to the correct second-stage unit, which handles up to 96 copper lines. The model provides 1344 lines, allowing for over 30 percent second drop requests. We assume that 20 percent of the households request a second drop.

We assume that the RDU is a buried, controlled environment vault. The RDU receives power from the local public utility, with power conditioning and eight-hour battery backup provided in the RDU.[1]

DISTRIBUTION LOOP

We assume underground construction throughout the distribution loop and the use of four cable sizes—600, 300, 100, and 50—pairs that are spliced together as necessary to cover the distribution area. Normal telephone planning rules for distributing copper call for large (e.g., 600 pair) cables to be laid for one or two blocks from the RDU, and then spliced onto successively smaller cables branching out at intersections. The model incorporates a similar design approach.[2]

DROP LOOP AND CPE

We assume that the cost of subscriber hookup is $80—equivalent to 1.6 hours of labor at a burdened rate of $50/hour.[3] The drop cable is assumed to be buried at a cost of $1 per meter. Two lines are installed to each home.

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[1]Luniewicz et al. (1984), p. 2327.

[2]Because the splicing costs for fiber are much greater than for copper, the fiber models involve multiple smaller fiber cables out from the RDU, terminating some on the nearby blocks and running others out to the perimeter. This eliminates the need for splicing within the distribution area other than for the drop cable to the subscriber.

[3]Estimate taken from Ensdorf et al. (1988).

TOTAL COSTS

As shown in Table E.1, the components involve a current total cost of $803 per subscriber, while future costs fall to $568 per subscriber. The future costs for the copper network are lower than most estimates we have seen.[4] A majority of future cost savings stem from cost reductions of the demultiplexing equipment at the RDU. We assume that improved VLSI technology will dramatically reduce equipment costs. This is in part justified by the fact that current costs of RDU equipment are based on digital loop carrier technology, which was introduced more than five years ago. Advances in VLSI will allow much more functionality with decreased costs.

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[4]Shumate (1989) asserts (without calculation) that the current cost of digital loop carrier lies between $900 and $1400 per home. If we include the costs of central office switching at approximately $200 per line (see Moondra, 1989), our current estimate of $1003 falls into the lower bound of this range.

Appendix F

FIBER NARROWBAND NETWORKS

ALL-FIBER NETWORK

Here we estimate the costs of an all-fiber active double star network for narrowband services. The central office, feeder loop, remote distribution unit equipment, and layout are identical to the network described for our copper/fiber hybrid in Appendix E. The distribution loop and drop loop equipment and layout are described in the active double star architecture in Appendix A.

The costs reported here correspond to the current and future cost figures reported for the copper/fiber hybrid. All cables are installed underground, as before. Cost totals are shown in Table F.1 for fiber costing $0.10 per meter.

Totals for other fiber costs (not disaggregated as above) are shown in Table F.2.

FIBER TO THE CURB

We also consider a network where the ONI is placed at the pedestal instead of either at the RDU, as is the case with a digital loop carrier system described in Appendix E, or at the customer's premises as in the above all-fiber narrowband network. This approach is often called "fiber to the curb," since the pedestals housing the ONIs typically are located in cabinets near a cluster of homes. Fiber to the curb has several advantages over the all-fiber narrowband network. It can

- Exploit the high capacity of fiber through sharing transmission facilities over more subscribers in the distribution portion of the network.
- Create a segment between the RDU and the pedestal for placing fiber in the network, while delaying fiber deployment in the drop.
- Postpone investment in drop plant where the telephone company already has a network in place—a significant saving because the cost of the drop plant cannot be shared over many subscribers.

Table F.1

COSTS OF AN ALL-FIBER NARROWBAND NETWORK
(In dollars)

	Current Cost	Future Cost	Cost per Home Passed: Current	Cost per Home Passed: Future
Central Office Equipment				
Optical transmitter,[a] optical receiver[a]	750, 300	60, 40	1	1
Multiplexer[a]	11,000	1000	15	1
Power[b]	10/watt	10/watt	1	1
Total			17	3
Feeder Loop				
Single mode fiber	0.20/meter	0.10/meter	5	2
Cable sheath	1/meter	2/meter	3	3
Cable installation	12/meter	12/meter	36	36
Inner duct	1.15/meter	1.15/meter	3	3
Splice, connector	40, 75	15, 25	2	1
Total			49	45
Remote Distribution Unit				
Optical transmitter,[a] optical receiver[a]	750, 300	60, 40	1	1
Multiplexer[a]	11,000	1000	15	1
Line interface unit[a]	193,600	83,600	265	114
Subscriber line card[a]	1070	110	1498	154
Wavelength division multiplexer[a]	100	35	140	49
Power[b]	15/watt	15/watt	45	45
Controlled environment vault	60,000	60,000	59	59
Total			2023	423
Distribution Loop				
Single mode fiber	0.20/meter	0.10/meter	160	80
Cable sheath	1/meter	1/meter	40	40
Cable installation	4/meter	4/meter	39	39
Inner duct	0.75/meter	0.75/meter	7	7
Connector	75	25	75	25
Pedestal/manhole terminal	100	100	13	13
Total			334	204
Drop Loop				
Fiber, sheath (per meter)	0.20,0.85	0.10,0.85	69	58
Cable installation (buried)	1/meter	1/meter	24	24
Splice, connector	40,75	15,25	2	2
Total			208	122
Subscriber Premises (incl. second drop)				
CPE (voice only)[b]	167	167	1182	167
Hookup and installation[b]	50/home	50/home	50	50
AC power outlet,[b] battery backup[b]	50/watt	50/watt	150	150
Total			1382	367
Totals				
Total electronics			3364	734
Total nonelectronics			650	430
Overall total			**4014**	**1164**

[a]Electronic component, marked up 40 percent over per item cost to cover field engineering, installation, and testing.

[b]Electronic component, per item cost includes installation and testing.

Table F.2

ALL-FIBER NARROWBAND NETWORK
FUTURE TOTAL COSTS
(In dollars)

Cost of Fiber ($/meter)	Cost per Home Passed
0.05	1117
0.10	1164
0.20	1257

Its disadvantages relative to the all-fiber network lie in the difficulties of upgrading to broadband service, which include:

- The bandwidth constraints imposed by electronics that limit the number of switched video channels.
- The possible need for expensive environmental protection of pedestals where broadband switching components are concentrated.

In our fiber-to-the-curb architecture, each fiber from the central office connects eight pedestals, each serving eight subscribers on an optical fiber bus. Thus, each fiber carries the narrowband traffic of 64 subscribers, equivalent in capacity at most to four DS1 (1.5 Mb/s) lines. This low bit rate reduces the level of environmental protection required by the pedestal electronics. Because the bus is two way, we assume that a fiber is dedicated for each direction of transmission.

The output DS1 signals of the switch are multiplexed at the central office onto the appropriate fiber for transmission to the eight pedestals on the fiber. At each pedestal, the downstream signal is converted briefly to electrical form to remove, using simple time division multiplexing, the signals sent to subscribers connected to the pedestal. The same process is required for the upstream signal to insert the signals from each pedestal onto the bus. Each subscriber requires a card to process the signal and convert it to analog format for transmission over copper wire pairs. We assume that each card can carry an N-ISDN signal (two voice channels and a 16 Kb/s data/signaling channel). The drop is the same as in our copper/fiber hybrid model in Appendix E.

Our estimates for the cost of power are based on the same assumptions that underlie the all-fiber narrowband model. The pedestal is connected to a commercial power outlet and houses the eight hours of emergency backup power required for voice service.

Table F.3

COSTS OF FIBER TO THE CURB
(In dollars)

	Current Cost	Future Cost	Cost per Home Passed	
			Current	Future
Central Office Equipment				
Optical transmitter,[a] optical receiver[a]	750, 300	60, 40	23	2
Multiplexer[a]	5000	500	109	11
Power[b]	10/watt	10/watt	10	10
Total			142	23
Feeder Loop				
Single mode fiber	0.20/meter	0.10/meter	30	15
Cable sheath	2/meter	2/meter	6	6
Cable installation	12/meter	12/meter	36	36
Inner duct	1.15/meter	1.15/meter	4	4
Splice, connector	40, 75	15, 25	8	3
Total			84	64
Optical Network Interface (Pedestal)				
Optical transmitter,[a] optical receiver[a]	750, 300	60, 40	368	35
Multiplexer[a]	5000	500	875	88
Line interface (framer)[a]	20	10	14	7
Subscriber line card[a]	50	22	70	31
Power—8-hour backup supply[b]	50/watt	50/watt	150	150
Total			1477	311
Distribution Loop				
Single mode fiber	0.20/meter	0.10/meter	14	7
Cable sheath	1/meter	1/meter	14	14
Cable installation	4/meter	4/meter	39	39
Inner duct and connectors	0.75/meter, 75	0.75/meter, 25	45	20
Pedestal/manhole terminal	300	300	37	37
Total			149	117
Drop Loop				
Drop cable	0.50	0.50	28	28
Cable installation (buried)	1/meter	1/meter	24	24
Splice, connector	1.67/splice	1.67/splice	2	2
Total			54	54
Subscriber Premises (incl. second drop)				
Protective block	30	30	30	30
Hookup and installation[b]	80/home	80/home	80	80
Total			110	110
Total electronics (including power)			1699	413
Total nonelectronics			318	266
Overall total			2017	679

[a]Indicates electronic component—marked up 40 percent to cover field engineering, installation, and testing.

[b]Electronic component, per item cost includes installation and testing.

Appendix G

RESIDENTIAL CABLE BROADBAND NETWORKS

For the comparisons in the text, we estimate the investment cost of an underground cable television network for the same service area assumed for integrated broadband networks. This appendix describes two models for a cable network providing one-way distributive services and includes the cost of the headend described in Appendix C.

CONVENTIONAL COAXIAL CABLE NETWORK

Network Design Rules

We calculate the investment cost of the coaxial cable network for a hypothetical service area containing 25,600 households—the same number as before.[1] To determine trunk and feeder lengths, we assume a uniform distribution of homes with a square grid of streets and rights of way throughout the service area. Consistent with our models of telephone networks, all network segments are assumed to be installed underground and, whenever possible, the trunk and feeder cables are placed in the same trench.

We apply several design principles common to the literature on the construction of cable television networks:[2]

- No subscribers are directly served from the trunk lines;
- No more than two feeder amplifiers are in cascade;

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[1]The layout for the conventional cable system is more compact than in our telephone network models. For the telephone network, we calculate the costs for an area consisting of 1024 households with a single remote node located 3070 meters from the central office (an average feeder length for the telephone industry). For the coaxial cable network, we assume that all 25,600 households (25 remote nodes of 1024 households each for the telephone network) are located side by side in a large square grid of streets (i.e., no long feeder segment is needed to reach the remote node). Consequently, the mean feeder loop length decreases almost one-half to 1660 meters—the 25th percentile of the total loop length distribution of the telephone network. However, the layout for the hybrid copper/fiber cable network, discussed below and used in our incremental cost analysis, corresponds exactly to that of our telephone models.

[2]See Baldwin and McVoy (1988), Chapter 3; Webb (1983), Chapter 3; and Rheinfelder (1970).

Table G.1

INVESTMENT COST OF COAXIAL CABLE NETWORK,
60 PERCENT VIDEO PENETRATION
(In dollars)

Network Component	Single Item Cost	Quantity	Cost per Home Passed	Cost per Subscriber
Headend equipment	243,100	64 channels	10	16
		Trunk		
Cable plant	3/meter	58.5 km	7	11
Field electronics	1550	100 sites	8	14
Passive components	230	100 sites	1	1
Installation	6/meter	58.5 km	14	23
Conduit	1.1/meter	58.5 km	3	4
Power system	1000	414	17	29
Total			50	82
		Feeder Loop		
Cable plant	1.6/meter	570.5 km	36	59
Field electronics	250	1600	22	36
Passive components	40	100	19	32
Installation	6/meter	439.5 km	103	172
Conduit	0.75/meter	439.5 km	12	22
Total			192	321
		Drop Loop		
Cable tap, connector	10,5	1	20	33
Cable plant	0.2/meter	27 meters	5	9
Installation (buried)	6.5/meter		11	18
Total			36	60
		Subscriber Premises		
Addressable converter	100	1	60	100
Second converter	100	20% + 10	18	30
Hookup, installation	50/home	1	30	50
Total			108	180
Overall total			**396**	**659**

Table G.2 breaks down the network component costs of the fiber backbone system for a system passing 1024 households—the same as in our IBN models. The costs of the optical transmitter and receiver units are similar to those reported by Baggett (1988) for transmission of 64-VSB-AM video signals. The costs for the remaining components are described previously in the IBN and coaxial cable models.

Table G.2

INVESTMENT COST OF FIBER-BACKBONE COAXIAL CABLE NETWORK, 60 PERCENT VIDEO PENETRATION
(In dollars)

Network Component	Single Item Cost	Cost per Home Passed	Calculation of Cost per Item
Headend Equipment			
Distributed video channels[a]	243, 100	10	64 distributed video channels (Appendix C)
Optical transmitter[a]	2500	3	Single laser transmitter of 64 channels (2500)(1.4)/(1024)
Power[b]	10/watt	1	Fixed cost of 0.1 watts per household (10)(0.1)(1024)/(1024)
Total		14	
Feeder Loop			
Single mode	0.10/meter	1	4 fibers of 3072 meters (4)(0.10)(3072)/(1024)
Cable sheath	2/meter	6	1 cable sheath 3072 meters (2)(3072)/(1024)
Underground cable installation	6/meter	18	Mean feeder length of 3072 meters (6)(3072)/(1024)
Inner duct	1.15/meter	3	Mean feeder length of 3072 meters (1.15)(3072)/(1024)
Splice, connector	15, 25	1	Each fiber spliced 3 times, 2 connectors 4[(3)(15)+(2)(25)]/(1024)
Total		29	
Optical Network Interface			
Optical receiver[a]	500	1	Broadband detector, 64 channels (500)(1.4)/(1024)
Amplifier, accessories housing[a]	1750, 100	2	One unit [(1750)(1.4) + 100]/(1024)
Power[b]	15/watt	5	1/3 watt per home passed
Total		8	

Table G.2 (Continued)

Network Component	Single Item Cost	Cost per Home Passed	Calculation of Cost per Item
		Distribution Loop	
Cable plant	1.6/meter	36	22.82 km of cable (22.3 meters/sub)(22820)(1.6)/(1024)
Field electronics[a]	250	22	64 feeder amplifiers (64)(250)(1.4)/(1024)
Passive components	10/connector 50/splitter	19	128 connectors, 256 splitters [(128)(10)+(256)(50)(1.4)]/(1024)
Underground installation	4/meter	68	17.55 km of trench (22.3 meters/sub)(17550)(4)/(1024)
Underground conduit	0.75/meter	13	17.55 km of conduit (22.3 meters/sub)(17550)(0.75)/(1024)
Power[b]	1000 per 3.2 km	15	Power station every 3.2 km over 50.9 km (50.9)(3.2)(1000)/(1024)
Total		173	
		Drop Loop	
Cable tap, connector	10, 10	20	
Cable plant	0.2/meter	5	27 meters drop cable per home (27)(0.2)
Cable installation (buried)	1/meter	11	11 meters common/dedicated trench
Total		36	
		Subscriber Premises	
Addressable converter[b]	100	60	(100)(0.6)
Hookup and installation[b]	50/home	30	(50)(0.6)
Second converter[b]	100	18	20 percent request second channel with $50 installation (150)(0.2)(0.6)
Total		108	
Overall total		**368**	

[a]Electronic component marked up 40 percent over per-item cost for field engineering, installation, and testing.

[b]Electronic component, includes installation and testing in per-item cost.

	Per Home Passed	Per Subscriber
Total	368	614
Electronics	167	279
Nonelectronics	201	335

Appendix H

COST OF POWER IN THE SUBSCRIBER LOOP

Unlike the case of a conventional copper network, the cost of power processing and distribution in a residential fiber network is likely to account for a sizable portion of overall investment. Metallic transmission media can generally carry enough electrical power to run network components; but optical fiber cannot carry enough power to perform this task. New arrangements will be needed to power the active components throughout the network, including customer premises equipment at decentralized locations, perhaps involving a dramatic increase in powering costs over those with copper.

This appendix reports our estimates for the cost of power to the network. We examine the current costs of copper and digital loop carrier power systems, and then present our methodology for estimating the costs of powering an all-fiber network.

GENERAL CONSIDERATIONS

Determining the best way to distribute and provide power to fiber networks may be one of the greatest engineering and economic challenges in bringing fiber to the home. Curiously, the topic has not received much attention in the literature. Yet, many believe power will be the major factor in finding the best network architecture for the subscriber loop. 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.[1]

The lack of discussion on powering stems in part from uncertainty about the power consumption of broadband electronic components. Broadband switching and multiplexing components are generally laboratory prototypes designed to demonstrate feasibility, not energy efficiency. Also, the degree to which the telephone company will be held responsible for powering network equipment is uncertain. Fiber to the home might require that residential subscribers be responsible for powering their own telephone equipment—an unprecedented

[1]Chynoweth (1988), p. 1.

situation for telephone service that would require new alternating current (AC) power outlets to be installed in customers' premises.

Fiber in the subscriber loop introduces two new complications to the network power system. First, because of network synchronization and performance requirements, network equipment will need to draw power continuously, rather than only when the circuit is used as in the case with copper. Second, decentralized electronics equipment must be powered, either by a direct connection to a local commercial AC power outlet, or by a separate copper network. In addition, emergency power must be be provided in case of a commercial power outage. These complications will arise in any subscriber loop network using fiber. There must be a point in the network where the conversion from optical to electrical transmission occurs—a location we call the optical network interface. Whether this interface is located at the RDU, the curb, or the home, it will require continuous and backup power.

To assess the life cycle costs of network energy requirements, the notion of the "worth of a watt" has been estimated to measure the net present value of energy and equipment costs associated with each watt of power consumption. That value is 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.

The cost of providing power to different locations throughout the network has been calculated in a number of studies. For a 30-year life cycle, Goldstein et al. (1978) estimate the worth of a watt at the output of the central office serving copper lines to be about $20. Mistry et al. (1989) estimate the worth of a watt to be roughly $25 at the remote distribution unit of a digital loop carrier system, and an astounding $165 for a fiber network extending all the way to the home. As expected, the worth of a watt increases with distance from the central office as the opportunities to share energy resources diminish. However, if powering the ONI proves enormously expensive, as estimated, it could preclude fiber to the home on economic grounds. If the customer drop were to consume as much as 5 to 10 watts for broadband service,[2] power system costs alone might have a present value of between $825 and $1650 over a 30-year period—almost as much as the installed first cost of the fiber network itself.

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[2]Chynoweth (1988).

However, advances in technology may lead to reduced power system costs over those reported by Mistry et al. For example, low-power, highly integrated opto-electronic integrated circuits and a powerdown mode when the equipment is not in use can greatly reduce power consumption. Moreover, economies of scale surely exist here so that, for example, the cost of supplying six watts would be less than twice that of supplying three watts. Consistent with our treatment of technological advances in other areas, many of our estimates below are optimistic about reduced power consumption and cost.

ESTIMATING THE COST OF NETWORK POWER

Copper Network

The energy needs of a copper network are a fraction of those required by fiber networks. The typical copper twisted pair draws between 1 to 3 watts when in use, which is about 1 percent of the time.[3] Backup power generators are needed for emergency situations, but the cost can be shared over all central office subscribers. Thus, even though the worth of a watt may be around $20 at the central office, the investment cost for power is under $1 per line.

Digital Loop Carrier

Digital loop carrier systems require much more power. Each line in such a system draws between 1 to 4 watts continuously—at least 100 times the energy for a copper system.[4] Digital loop carrier systems need power at the RDU, where the ONI consumes more than half the energy of the system to convert signals from the feeder fiber to the copper in the distribution loop. Thus, an RDU equipped with a stand-alone 48-volt power plant and eight hours of battery backup may cost $15,000.[5] Engineering and installation costs can almost double this figure. Moreover, power requirements are increased by the fact that DLC power delivery systems average only about 80 percent efficiency.

We have two components to consider in estimating overall power cost.

- *Central Office Power.* Goldstein (1978) calculates the cost of power at the central office to be roughly $20 per watt over a

[3]Taylor and Kimsey (1988), pp. 157–160.

[4]Ibid.

[5]Silverman (1988), pp. 320–325.

30-year period, of which about $10 represents the present value of operating costs. Thus, we assume capital costs to equal $10/watt at the central office.

- *Remote Distribution Unit.* Mistry et al. (1989) estimate the present value of power at the remote distribution unit to be about $25 per watt over a 30-year period. Again, assuming the present value of operating costs to be $10, we estimate capital costs of $15 per watt at the RDU.

Fiber to the Home

Fiber to the home can pose the same powering complications as do DLC systems, with the additional problem of powering the ONIs at the subscribers' premise. 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 all-fiber networks, we assume that 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 best method to provide power to the ONI is not yet clear. Three alternatives have been studied by Mistry et al. (1989):

- Power the network from the central office using the existing copper network to deliver electricity;
- Power the ONI locally (i.e., from the subscriber's power outlet) with local battery backup in the ONI;
- Power the ONI locally with battery backup located at the curb and connected to the ONI with a new or existing copper drop.

Mistry et al. (1989) failed to identify a dominant strategy among these alternatives. However, costs alone may not decide the best strategy; important network reliability and public policy objectives will also enter into the decision.

From a public policy perspective, requiring the subscriber to be responsible for both ONI power and battery backup may not be feasible. Consider the subscribers who want only the same reliable telephone service they now receive. As part of the installation of a fiber network, suppose that the telephone company installs an ONI box and new power outlet on the side of the house. If subscribers have the responsibility of maintaining emergency battery power, what are the chances that they will replace the batteries when they expire? An emergency situation during which perhaps 30 percent of the subscribers have no telephone service owing to expired batteries might be a regulator's worst nightmare.

For the telephone company, the task of maintaining batteries at every residence could hardly be viewed as an attractive responsibility. Yet the regulator might want to place the responsibility on the telephone company rather than the subscribers. If so, the telephone company may prefer to provide battery backup from the curb, rather than at each residence, to share more resources and ease maintenance costs. Regardless of how the backup power is provided, we assume that fiber networks must provide the same level of reliability for telephone service during a commercial power outage as is afforded today by copper networks.

Given the rough economic parity between the alternative powering approaches to the ONI as estimated by Mistry et al., we assume that the alternative of local power with backup power to the pedestal (curb) is the most likely for the following reasons:

- The telephone company would continue 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 collocate the ONI with the power supply at the pedestal to form a fiber-to-the-curb architecture. This approach would use the existing copper drop to carry narrowband services and coaxial cable to carry broadband services to the home. Thus, disruption to existing services in the home would be minimized.

Optical Network Interface

We assume that the ONI is located at the subscriber's premises and is powered locally, with backup power provided from the curb. AC power could be tapped directly from an AC utility pole, but we assume that a ring adapter is installed to the customer's energy meter, along with the wiring from the outlet to the ONI power supply.

The capital costs of powering the ONI has several components. Mistry et al. (1989) have provided a model by which we can estimate the costs of these components. Using this model as a guide, we estimate the capital cost to power the ONI to be about $50 per watt. Table H.1 illustrates how we arrive at this figure. The calculations are based on the assumptions that each pedestal connects to eight subscribers and that the efficiency of the power supply is 90 percent.[6]

[6]Sugiura et al., (1988).

Table H.1

CAPITAL COSTS OF POWER SYSTEM TO THE OPTICAL NETWORK INTERFACE
(In dollars)

Power System Component	Cost/Watt/ Subscriber	Description
Power transformer	6.9	Cost of $50 per watt shared over the number of subscribers per pedestal, with 90% power efficiency [(50/8)(1/0.9)]
8-hour battery backup	8.9	Batteries cost $1/watt-hour assuming a 10-year lifetime and 90% power efficiency [(8)(1)(1/0.9)]
Battery charger	5.0	Constant voltage charger to maintain batteries
ONI converter	5.0	
Power drop wire	5.0	Use the existing 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 locally powering the optical network interface and providing backup power from the curb

THE COST OF POWERING ALTERNATIVE NETWORKS

Table H.2 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. As was noted above, it is still uncertain just how much power each section of the fiber network will require in operation. Our estimates draw from current experience with DLC systems, taking into account the reductions in power consumption that can be achieved using more efficient engineering design.[7] As an example, Table H.2 shows a cost of $37 per subscriber to power a DLC system—$1 for central office power (with multiplexing, less then a tenth of a watt per line is necessary) and $36 for RDU power (2.4 watts per subscriber, which includes the 20 percent second line requests). We assume that second video lines do not appreciably increase power requirements in fiber networks.

Table H.2 also includes estimates for the costs of power systems in cable company networks. Using coaxial cable, power is needed to operate each amplifier in the network. Typically, cable systems have power units in convenient locations throughout the network that access

[7]Taylor and Kimsey (1988).

Table H.2

INVESTMENT COST PER HOME PASSED OF POWER SYSTEMS WITH ALTERNATIVE NETWORK ARCHITECTURES
(In dollars)

Network Alternatives	Type of Network Service			Cost by Network Location (Watt/Line)			
	Narrow-band	Distrib-uted Video	Switched Video	Central Office $10/watt	Remote Node $15/watt	ONI $50/watt	Overall Total Cost
Active Double Star							
Digital loop carrier	*			1	36		37
Narrowband on fiber	*			1	45	150	196
Voice and distributed video	*	*		1	60	250	311
IBN	*	*	*	2	75	300	377
Passive Double Star							
IBN	*	*	*	10		300	310
Switched Star							
IBN	*	*	*	40		300	340
Cable Networks							
				ONI	Trunk & Feeder		
Coaxial cable		*			17		17
Fiber backbone		*		6	15		21

the commercial power and multiplex the power onto the coaxial cable along with the television signals to operate other amplifiers in the area. A single power station is used for every 1–3 miles of cable.[8]

[8]The power to the ONI in the fiber backbone architecture is shared over all subscribers and backup power is not necessary. Thus, the cost is much less than that for telephone networks.

Appendix I

ESTIMATION OF THE ANNUALIZATION FACTOR

Here we provide the basis for annualizing our investment costs. Estimation of 13 percent and 17 percent annualization factors, respectively, for telephone and video service investment is based on procedures commonly used in government regulatory proceedings.

The "cost of money" (COM) is a weighted average of interest on debt and return on equity. It includes the effects of expected inflation but is net of taxes. The COM provides the basis for setting the authorized rate of return for telephone companies, typically in the neighborhood of 12 percent. The rate and tax factor (RIT) is the rate of return on new investment before taxes required to yield the COM after taxes. Thus, it includes the before-tax cost of equity return plus interest on borrowings. Ignoring the tax effects of accelerated depreciation, we have the following equations.

Nominal values:

$$\begin{aligned} \text{COM} &= di + r\,(1 - d) \\ \text{RIT} &= di + r\,(1 - d)/(1 - t) \end{aligned}$$

Real values:

$$\begin{aligned} \text{COM}^* &= d\,(i - p) + (1 - d)(r - p) = \text{COM} - p \\ \text{RIT}^* &= d\,(i - p) + [(1 - d)(r - p)/(1 - t)] = \text{RIT} - p\,(d + \\ &\quad [(1 - d)/(1 - t)]) \end{aligned}$$

We consider the following values, some of which are taken from an earlier study of telephone company experience in California.[1]

[1]Mitchell (1989). We take the values of d, i, r, and p from his study, but use a t of 0.40 percent for marginal federal and state corporate income taxes, in light of the current 34 percent marginal federal rate.

$$
\begin{aligned}
d &= 0.40 \text{ debt ratio} \\
i &= 0.0925 \text{ interest rate} \\
r &= 0.13 \text{ return on equity} \\
t &= 0.40 \text{ corporate tax rate} \\
p &= 0.03 \text{ inflation rate} \\
\text{COM} &= 0.4\ (0.0925) + 0.6\ (0.130) = 0.115 \\
\text{RIT} &= 0.4\ (0.0925) + [0.13\ (1 - 0.4)/(1 - 0.4)] = 0.167 \\
\text{COM}^* &= 0.115 - 0.03 = 0.085 \\
\text{RIT}^* &= 0.167 - 0.03\ [0.4 + (1 - 0.4)/(1 - 0.4)] = 0.125
\end{aligned}
$$

We round the annualization factor RIT* to 0.13 for our telephone analysis.

For video services we arbitrarily raise the interest rate i and the return on equity r by 3 percentage points, since we have no good data from regulatory proceedings or other sources for cable television figures that are based on the same ground rules as for telephone companies.

$$
\begin{aligned}
\text{COM} &= 0.4\ (0.1225) + 0.6\ (0.16) = 0.145 \\
\text{RIT} &= 0.4\ (0.1225) + 0.16\ (1 - 0.4)/(1 - 0.4) = 0.209 \\
\text{COM}^* &= 0.145 - 0.03 = 0.115 \\
\text{RIT}^* &= 0.209 - 0.03\ [0.4 + (1 - 0.4)/(1 - 0.4)] = 0.167
\end{aligned}
$$

We round RIT* to 0.17 for our video analysis.

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