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An Engineering and Policy Analysis of Fiber Introduction into the Residential Subscriber Loop

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by

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May, 1988

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Support for this research was provided in part by a grant to CMU from Bell of Pennsylvania.

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1. Introduction

The rapid development of fiber optic technology over the last 10 years has kindled the imagination of telecommunications researchers who have begun visualizing a wideband fiber optic network that reaches every household and provides the infrastructure for a vast range of new services. Trials of fiber optic networks delivering video as well as traditional voice and data services are underway in North America, Europe and Japan. [10, 35, 40, 26, 31] As the narrow band Integrated Services Digital Network (N-ISDN) moves from research to reality, Broadband ISDN (B-ISDN) has become the new holy grail.

For such a vision to be realized, numerous technical, economic, marketing and political barriers must be overcome. But the rewards for the telecommunications industry and its equipment manufacturers are dazzling. At an estimated $2000 per subscriber for wiring the nation with fiber optics, the capital costs alone exceed $200 *billion.*

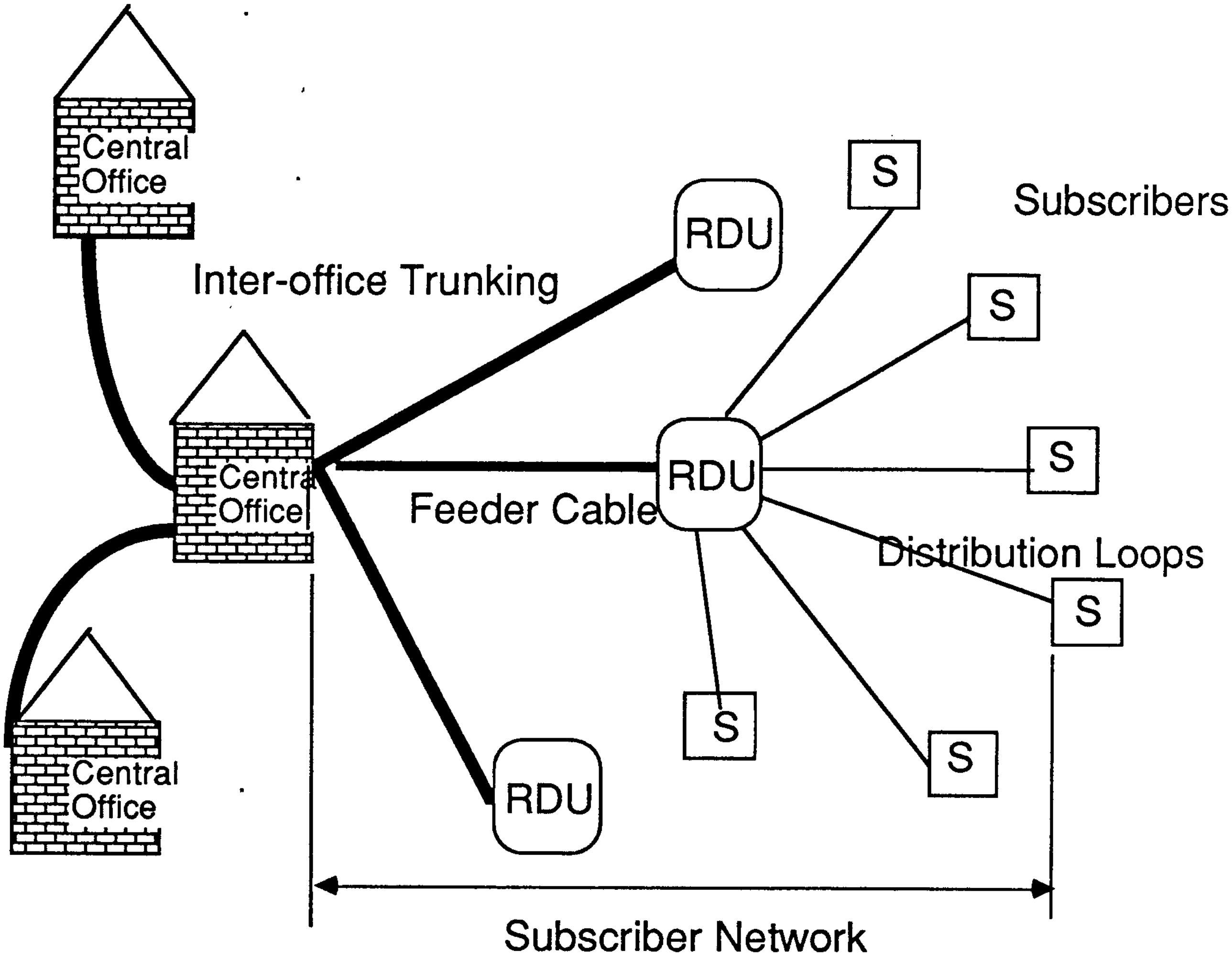
The successful implementation by the telephone industry of an infrastructure capable of readily delivering entertainment video, including video-on-demand, would create a powerful new competitor for CATV and over-the-air television, while creating entirely new options for "narrowcasting" or programming directed to small interest groups as opposed to a mass audience. The use of such a network for at last providing an acceptable "videophone" service could have profound sociological impacts.

In this paper, we present a preliminary analysis of the engineering, economic, and policy aspects of wiring the nation's residences with fiber optics. We focus on medium term (5 -10 year) technology options, and examine the economic implications of alternative architectures. Lastly, we consider several regulatory questions which are raised by our analysis.

1.1. Wideband Subscriber Networks

The development of fiber optic technology has been one of the most significant technological achievements of the past few decades. Today a single strand of glass fiber is used to carry digital signals at rates up to 1.7 Gbps -- the equivalent of more than 24,000 voice telephone calls or dozens of video channels, and the technology is still orders of magnitude below the theoretical limits. [37] Low attenuation reduces the need for repeaters to boost the signal over long distances. To date, fiber optics has been deployed primarily in the long distance network, where thousands of channels are needed between major switching centers. More recently, fiber has been used in local networks both for inter-office trunks and as feeder cable in the subscriber loop (Figure 1-1).

Figure 1-1: Telephone System Local Subscriber Loop Plant



By comparison, the ubiquitous copper wire telephone plant can carry signals of only a few megabits per second, and then only if costly-to-install repeaters are used every few thousand feet. It is not practical to use the existing copper plant for broadcast quality video. Current plans for narrowband ISDN stretch the existing copper plant to its limits to provide a mere 144 Kbps, full duplex, to each subscriber.

The installation of a fiber optic connection from telephone switching offices to every subscriber would provide the capacity for an almost endless array of new services: entertainment video, including high definition television; high speed data services; and of course, traditional voice service.

The design of such a network requires hundreds of engineering tradeoffs to be analyzed, including:

- Should switching be concentrated in large central offices with relatively long fiber optic loops to the customer, or should switching be more distributed, thus allowing less fiber, at the price of more instances of switching electronics?
- Assuming that video signals are digitized, what bit rate should be used? Higher bit rates mean cheaper codecs, but lower bit rates mean more signals can be multiplexed onto a feeder cable. What is the cost effective capacity of a fiber?
- What is the design time horizon? Should the system be architected based on 1990's technology, or technology expected by the year 2000? How different would the system look under each set of assumptions? Can one architecture migrate gracefully to the other over time?

In addition to these engineering questions, a number of economic and marketing questions must be addressed:

- What new service revenues would be required to justify retrofitting existing copper-served households with fiber? What services can be expected to generate these revenues?
- How long will it take to sign up subscribers for a new fiber optic network? How is the financial feasibility of a wideband network affected by assumptions about the time it takes to build up a sufficient subscriber base?
- How risky is an investment in a fiber optic network? Can capital spending be readily scaled to different rates of subscriber demand, or must the bulk of the investment be made up front?

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

- If entertainment video services are a key element in the financial success of a B-ISDN, how can the telephone companies deal with the limitations of the Cable Act of 1984, existing FCC cross-ownership restrictions, and the MFJ restrictions on information service offerings by the BOCs?
- What kind of franchise is needed from the authorities -- local, state and federal -- in order to install a new fiber optic local network?
- How can subscribers to existing copper-based services be protected from cross-subsidizing telephone company investments in fiber-based systems -- especially considering that the latter appears to fall under the classification of "basic" service, and thus will be lumped for accounting purposes with investments in copper-based plant?

1.2. Methodological Approach

In an attempt to shed some light on these questions, we have implemented an engineering/economic model of a residential subscriber fiber optic network.

Our analysis has focused on the costs of a Fiber Optic Residential Subscriber Network (FORSN) from the telco central office out to the subscriber's premises. As suggested in Figure 1-1, these costs include equipment at the local central office, feeder cable, remote electronics (if any), distribution cable, and network termination equipment on customer premises. While a complete analysis would look at the entire area served by a central office and optimize the number and locations of various remote distribution units (RDUs), our model considers only a single RDU and spoke emanating from a central office.

2. Architectures for a Fiber Optic Residential Subscriber Network: Design Options

As suggested in the introduction, there are many tradeoffs that must be made in designing a fiber optic residential subscriber network. In this section, we review the principal architectures being discussed for a FORSN, and examine the component technologies whose cost and performance characteristics ultimately determine the feasibility of an overall architecture. These component or subsystem choices can in turn be grouped under the following headings: Fiber and electro-optics, channelization, and location of switching.

Our analyses assume widespread introduction of an FORSN in the 1995-2000 timeframe. Consequently, in comparing technical options, we have made some allowance for the maturing of technologies which today are only available in prototype form. At the same time, some technologies, such as coherent modulation and detection have been judged sufficiently distant technologically, that we have not considered them in this analysis. [46] Similarly, we have assumed that widespread use of optical fiber for residential services will yield further reductions in cost below today's levels. Much as we have witnessed with N-ISDN, key circuit components will be implemented as single VLSI chips. Our technical and cost forecasts reflect these assumptions.

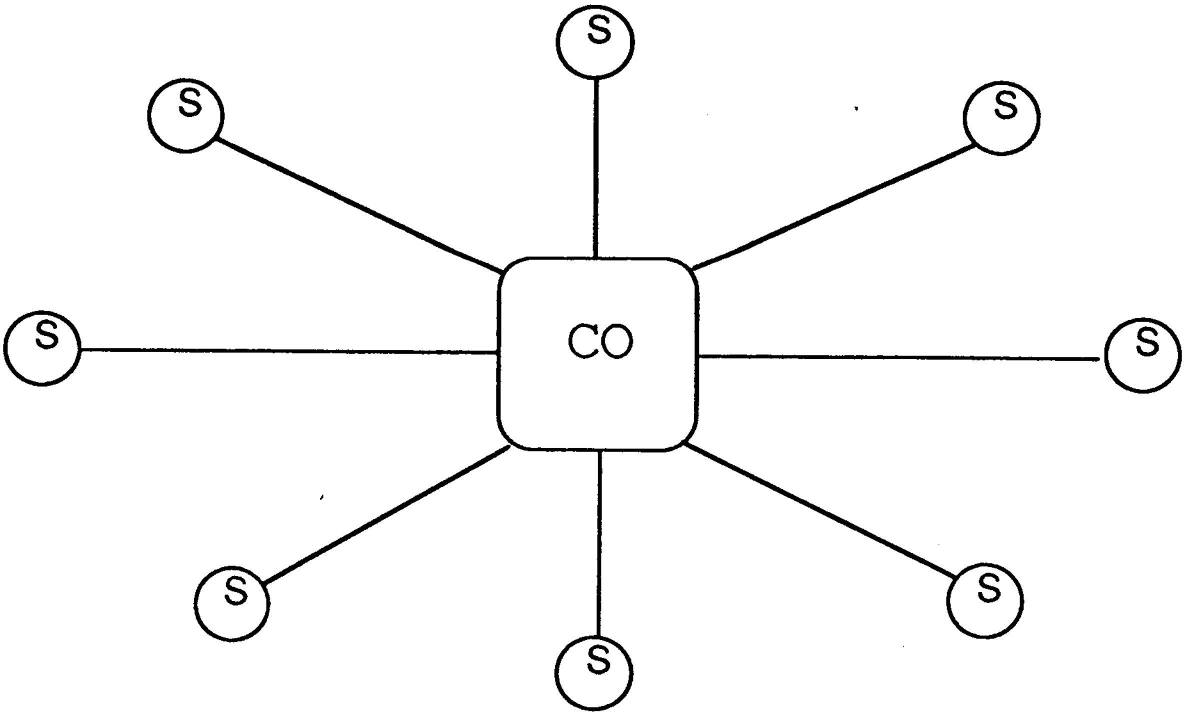
2.1. Alternative Architectures

The key decisions in any architecture revolve around where to put switching and multiplexing, and how to share transmission resources. The following examples illustrate the range of alternatives which have been presented in the literature.

2.1.1. Switched Star

At one extreme, researchers have proposed simple star networks, similar to the existing voice network. Individual fiber pairs would be laid from the central office to each subscriber, carrying signals for that subscriber only. All switching would be performed at the central office. In the limit, a separate fiber could be used for each video channel, in the event the subscriber has several televisions in use simultaneously tuned to different channels.(Figure 2-1). This design centralizes the switching electronics to take advantage of any economies of scale. The principal disadvantage is the amount of fiber required, since average loop lengths will be 4-5 kilometers, based on existing central office locations. This architecture makes the most sense when the cost of switching is high relative to the cost of transmission capacity.

Figure 2-1: Switched Star



2.1.2. Shared Fiber Bus

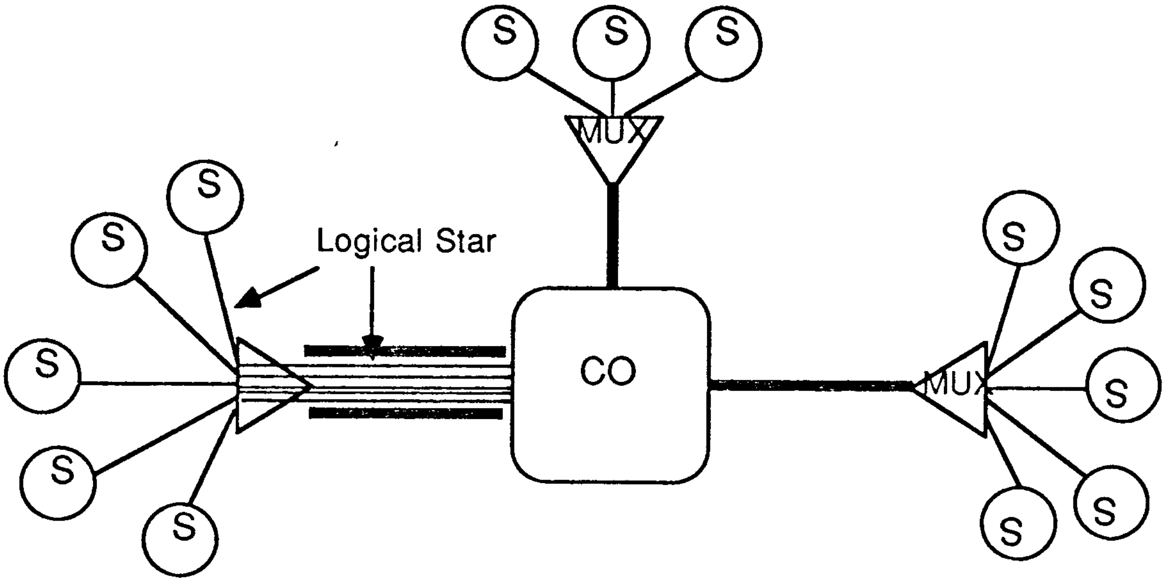
At the other extreme, a single fiber bus from the central office could carry television signals for dozens (--or, with coherent modulation techniques, thousands--) of signals to as many households by employing wavelength division or time division multiplexing. Optical splitters distributed along the bus would divert the signal to individual subscriber drops. Switching equipment on the subscriber premises would select out the subscriber's signal from among the many carried on the cable.

This architecture is similar to today's CATV systems. It is preferred when the cost of transmission is high relative to the cost of switching. While such a design economizes on fiber, it raises other problems. Tapping the bus frequently can lead to excessive signal losses, thus limiting the number of households that can be served. More expensive network termination equipment is needed to select the proper signal from the many carried on the cable. Adding subscribers without disrupting service to those farther down the line may be a problem. Problems in securing information privacy are also raised by having the signals of several subscribers come into each household.

2.1.3. Logical Star with Remote Multiplexing

As the previous example suggests, the amount of fiber required can be reduced dramatically by multiplexing several subscriber channels onto a high speed feeder fiber. In the logical star design, the feeders terminate in a remote multiplexing unit, and the individual subscriber's signal is carried the rest of the way on dedicated fiber. This configuration is similar to the ubiquitous digital loop carrier in today's copper telephone plant. Logically, such a network is a star, since each subscriber has a dedicated logical channel from his premises to the central office. Physically, however, it is a Double Star as shown in Figure 2-2.

Figure 2-2: Logical Star with Remote Multiplexing



The logical star reduces the amount of fiber through multiplexing, with pair gain on the order of 12-30 depending upon bit rates in the feeder and distribution cables. Because the final distribution fiber carries signals for only a single household, there is no security issue as in the previous design. Additional subscribers can be added with no disruption of service as with bus systems.

Multiplexing can be by either wavelength division (WDM) or time division (TDM). If TDM is used more costly electro/optical interfaces and electronics are needed to handle higher speeds on the feeder cables, and for the multiplexors. If WDM is used, the multiple wavelengths must be filtered and sent to the appropriate distribution cable. The use of multiple wavelengths implies that subscriber equipment may not be standardized, but will vary according to the assigned wavelength. This can cause problems of inventory and maintenance. The alternative, a receiver capable of receiving any of a number of wavelengths is more costly.

2.1.4. Active Double Star

The amount of fiber in the feeder plant can be further reduced by deploying active switching units in the RDU. When multiple subscribers want to watch the same network TV broadcast simultaneously, a logical star must carry the same signal over the feeder cable many times. An active remote switching unit could take one copy of the network broadcast from the feeder cable and replicate it onto the distribution fiber of many households. (See our discussion of the demand for video services in section 3.2.)

2.1.5. Passive Double Star

The light signal on a fiber can be split optically onto two or more fibers by simple passive devices. In a Passive Double Star, the signals for several households are multiplexed -- by either time division or wave division, or both -- onto a single fiber at the central office. At the RDU a passive splitter replicates the optical signal onto individual distribution fibers. Equipment at the subscriber's premise is directed to select the correct signal from the several multiplexed on the fiber. Configuring the network as a double star rather than as a bus simplifies maintenance by locating the passive splitter at a single well defined point. Also, there is less excess signal loss from a single 1:n splitter than from a succession of taps on a bus, thus allowing more subscribers to be served within the available signal power. However, the passive double star, like the Shared Fiber Bus, suffers from the same security problem and the need to have signal selection equipment on the subscriber's premises.

2.2. Component and Subsystem Issues

One cannot choose readily among these architectural alternatives without examining in more detail the choices available for the component technologies, and their economics. Thus, we turn now to a consideration of the subsystem choices which taken together determine the merits of particular architectures.

2.2.1. Fiber and Electro/Optics

Two types of fiber are in widespread use today: multimode and single mode. Multimode fiber, which typically has a core diameter of 62.5 microns is used primarily in local area networks and intra-building applications. It's large core diameter makes for easier splicing and allows better coupling with low-power sources such as inexpensive light emitting diodes (LEDs); it is also simpler to fabricate than single mode fiber. The principal drawback is that its information carrying capacity decreases sharply with distance by comparison with single mode fibers. Single mode fiber, with a 5 micron core, is the preferred choice for the interexchange network, where high channel capacity over long distances is desirable. Competition has led to the rapid introduction of single mode fiber (SMF) by U.S. Sprint, MCI and AT&T with the result that SMF costs have declined to be equal or even lower than multimode fiber. [33]

In the subscriber network, short loop length (90% of all subscriber loops in the U.S. are under 10 km.) and suggestions that subscribers may not need the larger capacity of single mode fiber have led some to propose the use of some multimode fiber for subscriber loop applications. [10, 21] Others have argued that installation now of single mode fiber, even if it is more costly at first, allows greater opportunity for future expansion of services not now anticipated. [8, 25].

In our analyses, we have assumed that single mode fiber will be the medium of choice throughout the subscriber loop plant. Based on a variety of sources, [45, 27, 15] we assume that SMF will be available at a price of $0.10/meter. Since this is a critical parameter we have examined alternative prices of 5 and 20 cents per meter. Current costs are in the vicinity of $.30/meter. [27]

In general, SMF with the lowest possible attenuation loss is more costly than fiber with higher attenuation. In the interexchange network, repeater costs can be reduced by deploying the lowest loss fiber; over the shorter distances found in the local loop, repeaters are typically unnecessary, and, it may not be worth the premium cost of extremely low loss fiber. [30] We assume attenuation and dispersion losses in the fiber amount to 1.0 dB/km.

Another cost trade-off issue involves the splicing and connecting of SMF. The cost of splicing and connectors increase with the accuracy of alignment. For example, misalignment of the fiber cores by 1µm to 3µm in a connector increases the losses from a few tenths of a dB to 2 dB, respectively, while decreasing the cost of the connector by a factor of three [3]. We assume losses of roughly 2 dB/connector and 1 dB/splice. The cost of installed connectors we have included explicitly at $27.50 each; splice costs vary depending upon whether single fibers or ribbon cable is being spliced.

Related to the choice of fiber is the issue of optical transmitters and receivers. Expensive laser diodes (LDs) are used throughout the inter-exchange fiber networks to achieve greater power input, allowing longer distances between repeaters. Light emitting diodes (LEDs) offer a less expensive and easier to manufacture alternative. [16] However, they are typically limited to bitrates of 200 Mbps and transmit considerably less power into the fiber. However, recent research suggests that edge-emitting LEDs can be used at bit rates as high as 560 Mbps over single mode fiber with adequate power coupling for local loop applications. [18] At the same time, widespread production of inexpensive LDs for use in consumer compact disk players suggests that the cost of lasers for telecommunications applications could be sharply reduced in the future. Thus, the choice of LDs versus LEDs depends upon forecasts of future costs for each component type, as well as considerations of durability, power level required in a particular configuration, and the peak bit rate. [20]

Based upon the compact laser disc experience and private discussions [36] , we assume that the cost of a source operating at 600 Mbps or less will be $25, regardless of whether a LD or LED source is used. Laser diodes are used for feeder cables multiplexed to bitrates above 600 Mbps and the cost of a complete laser diode transmitter, suitable for mounting on a printed circuit board, including pigtail coupling, is assumed to cost $100. [16, 1]

The alternative photodetectors available include the higher cost avalanche photodiodes (APDs) and the less expensive PIN photodiodes. Since the signal generated in the APD is internally amplified, the APD can detect lower optical power levels than the PIN photodiodes. PIN photodiodes are used for systems using low to moderate bitrates, while APDs are used for high bandwidth applications (typically greater than 1.5 G bps). [11] APDs are also more sensitive to temperature variations. The former we estimate to cost $100 each; [42] the PIN photodiodes $25.

The combination of optical sources and detectors to be used in a given configuration is determined by the optical power budget. In our analyses, we chose the cheapest combination of components which met the desired power margins. Edge-emitting LEDs are chosen over LDs, just as PIN photodiodes are chosen over APDs whenever the optical power levels made the exchange possible.

Finally, there is a choice between deploying two fibers to every subscriber -- one for each direction -- or to use a single fiber together with wavelength division multiplexing (WDM) -- a different frequency light source for signalling in each direction. Again, the tradeoff pits savings in fiber cost against the cost of the WDM equipment. [20, 2, 41] Our analysis suggests that it will be cheaper to use WDM on the distribution fibers, while designing for separate fibers in the feeder segments. We have estimated the cost of wavelength division multiplexors/demultiplexors at $45 per port at each end.

2.2.2. Channelization

The wideband fiber into the home can carry a number of different services. How should these be multiplexed on the fiber, and what should be the standard data rates? The key tradeoff in setting these rates is between the capacity used, and the cost of signal processing and compression. For example, an NTSC video signal can be very cheaply digitized at 120 Mbps. [6] However, by investing in more costly encoding equipment, the signal can be reduced to 45 Mbps or even less. How important is it to save bandwidth at the price of more costly electronics? Should signal quality be reduced to simplify coding?

The tradeoff is rendered even more complex by the need to anticipate other services besides NTSC video -- Extended Quality Television (EQTV), or High Definition Television (HDTV) are two examples. While the cost of transmitting an NTSC signal at 45 Mbps may be reasonable, compressing an HDTV signal to that rate would be extremely costly and perhaps technically infeasible. Users may also want access to high bit rate packet data services. Bellcore [8] has even suggested that voice traffic be packetized and sent over a high speed packet data channel.

A wide range of proposals have been suggested in the literature for the channelization of fiber to the home. [8, 22, 39, 4] We have chosen to consider two proposals in detail.

- The first option calls for a standard B-ISDN channel of around 150 Mbps, with the typical subscriber receiving up to four such channels for an aggregate data rate of 600 Mbps. [8, 25] A 150 Mbps channel can be used for an NTSC signal with no compression, while carrying HDTV with only modest compression. The four channels would be interleaved on a bit by bit basis according to the proposed SONET multiplexing scheme. [7] The choice of 150 Mbps as the basic video channel rate has gained support in recent CCITT discussions of standards for B-ISDN. [38]
- The second approach calls for video channels of roughly 44-45 Mbps (fitting inside current DS3 channels). The lower bit rate allows for more effective fiber pair gain when using passive splitters.

In both cases, we visualize an equivalent N-ISDN basic access rate or primary rate interface being multiplexed with the video channels. This allows the use of existing N-ISDN switching capacity, rather than replacing such capacity with, for example, wideband packet switches for both voice and data. Indeed, during the early trial deployment of fiber in old neighborhoods, voice may continue to be carried on existing copper pairs. Only in new construction should we expect to see all-fiber networks.

While considerations of electronics and transmitter/receiver costs limit total bit rate dedicated to a household to the 600 Mbps range, feeder cables may operate at considerably higher rates. Trials are currently underway in the long distance network of 1.7 - 2.24 Gbps equipment. [17] In the 1990s, we forecast a typical feeder rate of 2.4 Gbps, and consider rates as high as 5 Gbps.

2.2.3. Switching and Multiplexing

Switching video signals at 150 Mbps requires significantly different approaches than switching voice at 64 Kbps. Today's digital exchanges multiplex many voice conversations onto a high speed bus and then use time slot interchange to switch connections. Such an approach is prohibitively expensive for 150 Mbps channels. [39] The most widely proposed alternative is a space division switch with crosspoints implemented in a VLSI circuit. Several investigators [8, 39, 4, 13] have demonstrated prototype switching matrices capable of operating in the 150 Mbps range which is the peak rate envisioned for a video channel. Bellcore, for example has implemented a 16x16 cross point as a single integrated circuit of about 25 mm^2 in 2μ technology; and a 64x64 switch with all drivers, receivers and control logic has been built on a single card. [9] It appears, therefore, that relatively inexpensive switching for 150 Mbps digital video channels can be realized. In quantity, a CMOS chip of 25 mm^2 in 2μ technology can be produced for under $5 today. Thus, we believe that a 64x64 switching card will cost no more than $200, assembled and tested.

Multiplexing is the other key electronic technology. Several architectures call for multiplexing multiple video channels at rates up to 2.4 Gbps on feeder cables. These rates exceed the capabilities of CMOS technology, calling for gallium arsenide components of only medium scale integration. As a consequence, we believe such multiplexors will be considerably more costly than switching matrix components. We have estimated that such multiplexors will cost from $1200 - 2400 in large volume production.[1] It is for this reason that designs which call for TDM demultiplexors at the network termination point (e.g. passive star) are limited to bit rates far below the 2.4 Gbps capability of current optical fiber transmission systems.

A reasonable peak data rate for a CMOS/bipolar multiplexor is around 600 Mbps. Bussey has constructed such a multiplexor for combining up to four 150 Mbps channels to a subscriber in a single VLSI chip, plus an additional chip for framing and synchronizing the four channels. [8] Even where a subscriber receives only one video channel, such a multiplexor is needed for integrating a video channel with N-ISDN service channels. Based on these prototypes we have assumed that a subscriber line interface card containing multiplexors and framing, and LED optical transmitters for up to four subscribers can be fabricated on a single card at a cost of roughly $275.

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[1] The cost for such multiplexors also increases with the number of channels as a result of increased pin out, drivers, etc.

3. Models and Assumptions

To analyze in more detail the tradeoffs associated with the design of a FORSN, we have constructed a simple engineering cost model for one quadrant of a network (Figure 1-1). The model assumes a central office providing N-ISDN and B-ISDN switching. We have looked at three alternative designs:

- Switched Star
- Active Double Star
- Passive Double Star

In the first model, fibers lead directly from a central office to the subscriber. In the other two models feeder fibers emanate from the CO and terminate in a Remote Distribution Unit which contains either active or passive equipment, according to the model. Distribution fibers provide the final link to the subscriber.

We have focused on the case where fiber is being overbuilt in a neighborhood already serviced by copper, since this will ultimately be the most common case. The RDU is assumed to service an area having a maximum of 1000 potential subscribers, although not all households are assumed to subscribe to fiber-based services. Those who do not subscribe have N-ISDN services provided over the existing copper plant, whose costs are assumed sunk. We also treat as sunk the costs of N-ISDN switching; switching costs at the CO include only the incremental costs to support video switching. Thus, the costs of fiber installation and related electronics must be born by only those subscribers who sign up for fiber-based services, of which the principal service is expected to be entertainment video. In particular, we assume that enough distribution fiber is installed to handle every household should they eventually choose to subscribe. While this minimizes installation labor, it implies a substantial initial capital investment in fiber. Similarly, enough feeder fibers are installed initially to handle 100% penetration. Depending upon the rate at which subscribers sign up, it may be cheaper, in present value terms, to defer some fiber installation, even though going back to reinforce an existing installation has higher labor costs than installing it all at once.[2]

The distance from the CO to the subscriber is based on data from two sources: Hightower provides a complete distribution of working loop lengths for the BellSouth region (Figure 3-1); [22] Singh provides mean working loop length, feeder length and distribution length based on the 1983 Bell System loop survey. [43] For our models we used the shape of the distribution from Hightower, but adjusted the mean feeder length using the data from Singh.

The costs of installing fiber from an RDU to the subscriber can vary widely depending upon whether it is an urban neighborhood of high rise apartments or a suburban neighborhood with single family houses

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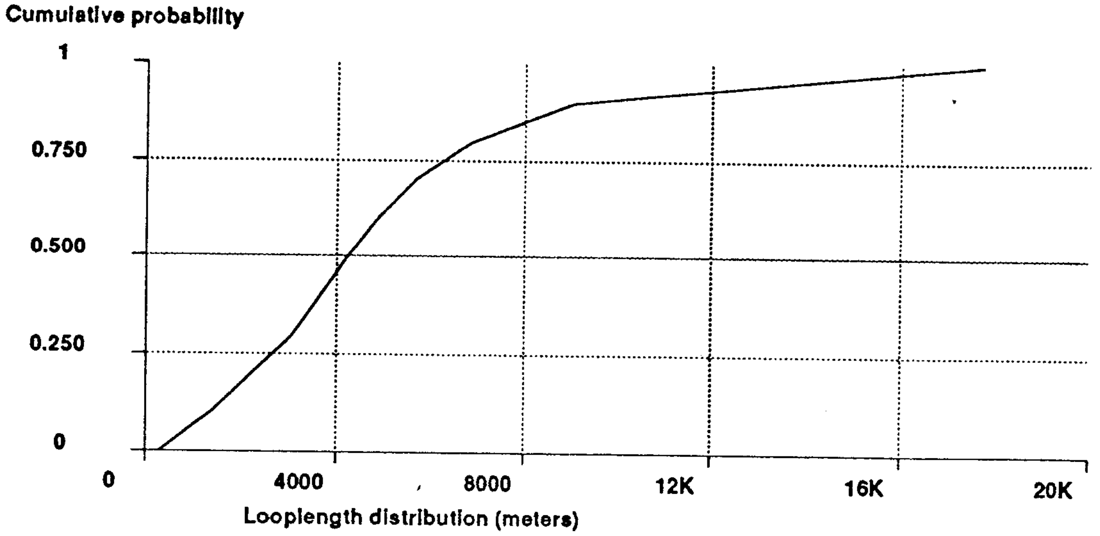
[2] In a related study, Sirbu and Reed [44] have developed a model for determining the optimal time to begin investing in fiber to the home based on forecasts of future component cost reductions, and the opportunity costs of deferring potential income from fiber based services. Preliminary results from this model suggest that for real discount rates up to 9%, and in the absence of pressure from competitive fiber installation by the cable companies, the optimal time to begin widespread deployment of fiber to the home would be around 1994.

Figure 3-1: Cumulative Distribution Function for Working Length from CO to Subscriber for the BellSouth Region



on two acre lots.

To obtain a representative value for the costs of the network between the RDU and the household, we assume the following:

- The serving area under consideration contains approximately 1000 households in a neighborhood laid out as a grid of six square blocks (and including both sides of the street on the outer perimeter); each block contains 24 living units.
- Lot size and average block length have been chosen to result in a typical density of 100 units per linear street mile (counting both sides).
- The RDU is positioned at the center of the serving area.

Normal planning rules for copper would call for large (e.g. 1200 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 root and branch layout is typically done by hand based on standard design rules, such as the number of growth pairs to allow per household. We have performed a similar design for the fiber distribution cable in our models. However, because splicing costs are so much larger for fiber than for copper, we have chosen to run multiple smaller cables out from the RDU, terminating some on the nearby blocks and running others out to the perimeter. This eliminates the need for splicing, other than for the drop cable to the subscriber.

We also assume that the fiber optic cables will only be available in certain sizes. At present, there are no standard sizes for fiber optic cable for use in the distribution loop; we have thus selected standard sizes convenient for our models. For example, in the star and active double star architecture, we assume that a standard fiber cable contains 36 fibers. In the passive double star, cables are available only in multiples of 12 fibers. A protection factor specifies the percentage of dark fiber which is installed to cover either fiber failures or growth in the future. Inner duct is installed for each distribution cable.

Drop cables are spliced to the distribution cable and run from manholes (assumed to be spaced one or two per block) to the residence. Drop cables are installed without inner duct but with a rodent-proof sheath.

In all of our models customers are provided with downstream video services, and full duplex N-ISDN services. *We have not considered upstream video from the home, as would be required for videotelephony.* We have made this assumption in our effort to identify a fiber system capable of competing with CATV, but with the lowest possible entry cost.

3.1. Active Double Star

We shall consider the Active Double Star model first, both because it illustrates most of the technologies we have examined, and because it has received a great deal of attention, particularly from Bellcore. [8, 25]

Video signals and N-ISDN signals arrive at a central office on incoming trunks. The standard data rate for a video signal is 150 Mbps; N-ISDN services are at the basic access rate of 144 Kbps. Separate switching matrices are assumed to be used for each signal (Figure 3-2). The outputs of each switching matrix are time division multiplexed onto feeder fibers from the central office to the RDU. Two fibers are dedicated to carrying multiplexed N-ISDN traffic: one in each direction. As many fibers as are necessary to carry the estimated peak demand are devoted to downstream video traffic. Feeder fibers operate at 2.4 Gbps.

At the RDU, the video signals are demultiplexed and fed to a remote switching unit based on CMOS cross-points operating at 150 Mbps. The N-ISDN signals are simply demultiplexed, with no remote switching assumed. Up to four video outputs are then multiplexed together with an N-ISDN basic rate interface for transmission on the distribution fibers to the subscriber (Figure 3-3). An upstream channel is needed for the N-ISDN traffic. Rather than supply two fibers to every household, we assume that a single fiber is used together with wavelength division multiplexors at the subscriber's premises and at the RDU.

At the subscriber's premises, the signals are demultiplexed, and the digital video signals are converted to analog for a standard TV (Figure 3-4).

Call set-up for both voice and video is assumed to be conveyed via the N-ISDN D channel to the central office. The CO then insures that the correct video signals are sent to the RDU and controls the video switch in the RDU to send the correct signal to the subscriber's line.

Figure 3-2: Central Office Configuration

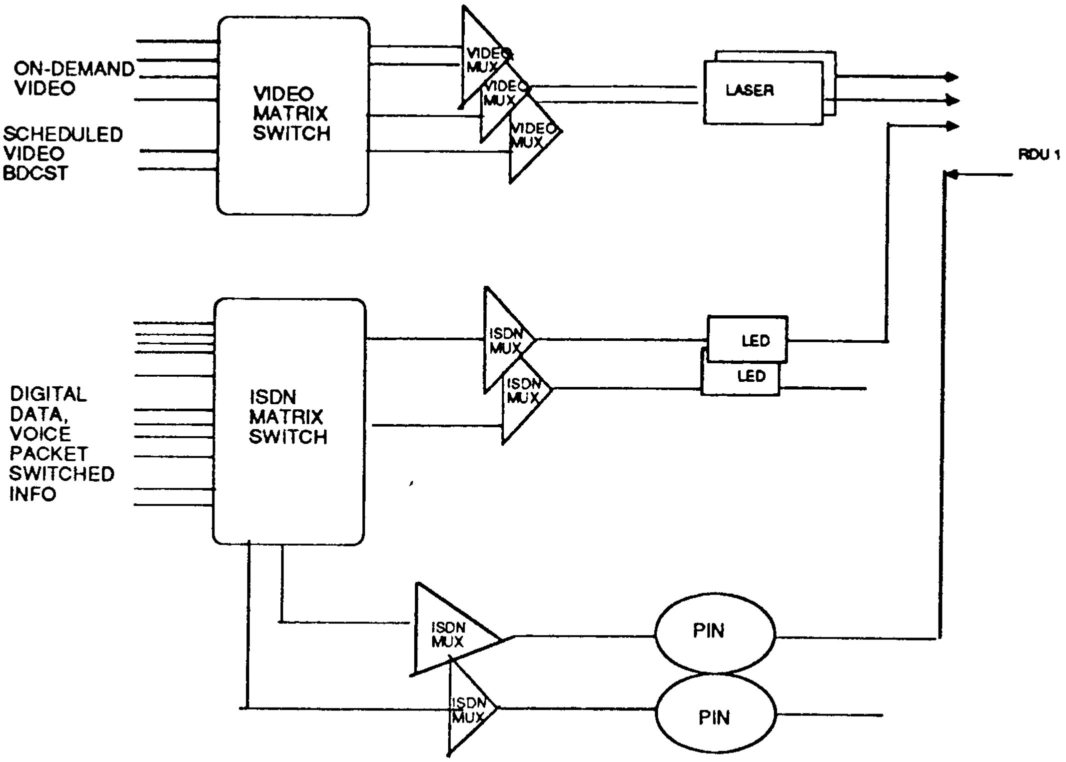


Figure 3-3: RDU for Active Double Star

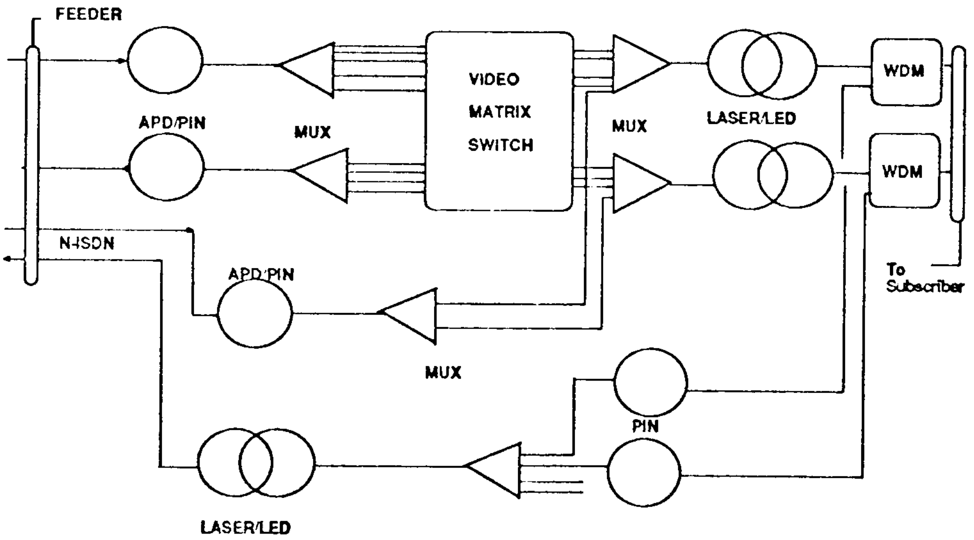
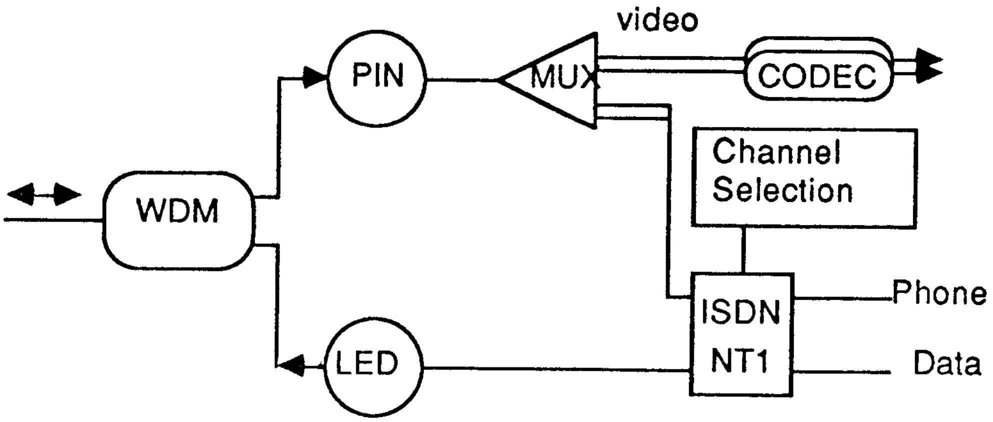


Figure 3-4: Subscriber's Premises Equipment



3.2. Demand for Video Services

While much has been written regarding future services to the home, [24] we believe the principal source of revenue to cover the cost of installing fiber will be the delivery of entertainment video. Indeed, many of the new services which have been described in the literature can be delivered perfectly well via N-ISDN over copper loops. Only moving images require the bandwidth of fiber.

Video services can be of two types: *Distributive* video, in which a common broadcast signal is delivered to many households simultaneously, and some form of *Video on Demand* in which the subscriber receives a unique signal meant only for him or her. An example of the latter would be a subscriber dialing into an automated videodisk "jukebox" to receive a particular movie.

Estimating the number of subscribers who at any one time will prefer to watch distributive video versus on-demand video is critical to sizing the feeder plant and the remote switching unit. For example, assume that during the peak hour some 500 subscribers served by an RDU are watching television. As many as 90% may be watching one of the four major networks or other continuously broadcast channel such as HBO or ESPN, while 10% are watching some unique program. In an active double star network, only 6 channels would be needed on the feeder fiber to carry the distributive video signals watched by 90% of the subscribers, while 50 additional channels will be needed to carry the on-demand video requested by the remaining 10%.

Our model assumes that 36 channels of distributive video are automatically provided to the RDU from the central office. Requests for distributive video programs beyond these 36 channels are handled the same as demand-video requests.

We desire to provide enough channels between the CO and the RDU so that the probability of no channel being available to service a request is below some set Grade of Service (GOS), typically .01. We assume that a request can be serviced by any available channel; however, if there are no available channels, the requestor goes away.[3]

3.2.1. Estimating the Traffic

We must estimate the offered traffic A in order to determine the number of necessary servers K given some predefined grade of service. In the absence of any commercial experience with on-demand video, we assume that VCR owners approximate the viewing habits of potential on-demand viewers in order to estimate the average offered video traffic. According to the AC Nielsen Co., in 1984 the average owner of a VCR will, three years after purchase, watch 42 minutes per week of video cassettes or about 2 movies per month. [12]. We have explored a range of values up to 3 hours/week.

Not all video requests will occur during the peak busy hour--only a percentage of the weekly average. Our model assumes 20% of the weekly minutes are viewed during the busy hour, *e.g.* 8:30pm - 9:30pm on a weekend night. This compares to a mere 0.59% if the traffic were uniformly distributed over the 168 hours in a week. We must also allow for the possibility that there is more than one television in use in a household, each tuned to a different program. Hightower notes that some 15% of CATV subscribers have a second drop. In our model, we have assumed that second, third and fourth drops increase the total number of users by 20% over the base number of households subscribed; however these additional drops are assumed to generate requests for on-demand service at half the rate of the primary drops. We use standard tables of Erlang B values to derive the number of channels *k* necessary to meet the grade of service objective.

3.3. Central Office Star

The simple star model uses switching and channelization quite similar to the active double star. The principal difference is that video switching takes place only at the CO, and a fiber runs directly from the CO to the subscriber's premises.

The CO is assumed to provide up to four 150 MBPS video channels to each subscriber. These channels are multiplexed onto a single fiber for each subscriber along with N-ISDN traffic for voice; wavelength division multiplexing allows the use of the same fiber for the return N-ISDN channel. In this model, loop plant is not dependent on the level of Video-On-Demand service requests.

Equipment at the subscriber's premises is the same as for the active double star.

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[3] This is usually referred to as a full availability, loss system. For alternative models which assume that the caller retries within a short time interval see [28]

3.4. Passive Double Star

The third model we have analyzed in detail is the Passive Double Star. As described in Section 2.1.5, in the passive double star architecture, video signals for several subscribers are multiplexed onto a feeder fiber from the central office. At the RDU, a passive optical splitter replicates the combined signals onto *h* distribution fibers which carry them to network termination equipment (NTE) on the subscriber's premises. The NTE then demultiplexes the signals and presents the subscriber with his particular selection.

The number of households, *h*, which can be served from one feeder fiber depends upon two factors: the number of distinct video channels, *M* which can be carried on the fiber, and the statistics of viewing which determine the number of distinct channels *D* needed to service a group of *h* subscribers with grade of service α.

In the active double star design, the video channel rate was set at 150 Mbps in order to minimize the cost of video codecs. Multiplexors on the subscribers premises were limited to 600 Mbps. If these rates were applied to the passive double star, only four distinct channels could be provided by one fiber from the central office. Increasing the data rate on the fiber would require more costly demultiplexors in the subscriber's network termination equipment. A better approach would be to use moderately more costly codecs to reduce the video channel rate to 45 Mbps, while keeping the TDM rate at about 565 Mbps. While 45 Mbps is adequate for NTSC video signals, it may be inadequate for EQTV or HDTV. Nevertheless, this architecture economizes substantially on fiber by comparison with a single star, while minimizing the cost of equipment in the RDU. [22] Moreover, it does not require the development of video switches capable of operating at 150 Mbps rates. This approach can be viewed as one which is more easily achievable with current technology, while potentially more limiting in terms of future demands for HDTV.[4]

3.4.1. Households per Fiber

A fiber running at 565 Mbps with 45 Mbps per video channel has a capacity of 12 channels. How many households can be served by these 12 channels? Our first inclination was to follow the suggestion of Hightower [21] and attempt to analyze the statistics of video viewing. Recognizing that multiple households might desire to watch the same network programming, and that they could all be served from the same channel, one might attempt to calculate how many households *h* can actually be served by *M* channels with grade of service α. An analysis along these lines, using viewer statistics from A.C. Neilsen, [32] suggested that 12 channels might actually be adequate for up to 22 households with $\alpha=.01$.

Upon reflection, however, we observed that most CATV viewers from time to time scan most or all of the available channels, for example during network commercials. To the extent that three viewers of the same network program decide to scan the channels at the same time but in a different order, it takes not one but three distinct channels on the fiber to insure their ability to do so, despite the fact that most of the

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[4] It is possible, of course, that the development of coherent modulation and detection technology will, in the future, make it economical to use wave length division multiplexing together with a passive star architecture to provide higher channel rates to each subscriber. Thus, the passive star physical network may well prove readily adaptable to 21st century technology.

time one channel is sufficient. Since it seems unlikely from a marketing perspective that a system builder can afford to deny customers the right to "spin the dial", we are left with the conclusion that there is no opportunity for gain due to call statistics.

Thus, if M is the number of channels per fiber, and S is the fraction of additional channels per household which will be viewed concurrently with the primary connection, then, $h = M/(1+S)$.

4. Results

We have run our model using the basic assumptions detailed above, together with a few sensitivity analyses in an attempt to better understand the economics of a fiber optic residential subscriber network.

4.1. Active Double Star

A key question, of course, is the total capital cost per subscriber to provide fiber-based services. We focus here on the *incremental* capital that must be invested to provide service over fiber as opposed to copper, and to provide video as well as voice. Thus we include all investments in fiber loop plant and new investments at the CO to support video switching. As noted earlier, we consider the costs of narrowband ISDN switching as sunk, and therefore they are not included.

In practice, much of the capital must be invested up-front, before it is known how many residences will choose to subscribe. Consequently, the cost per subscriber depends strongly on the assumed penetration rate. Figure 4-1 shows the average cost per subscriber as a function of the percent penetration, for various estimates of fiber cost per meter. We have assumed 1.5 hours of video on demand viewing per subscriber per week.

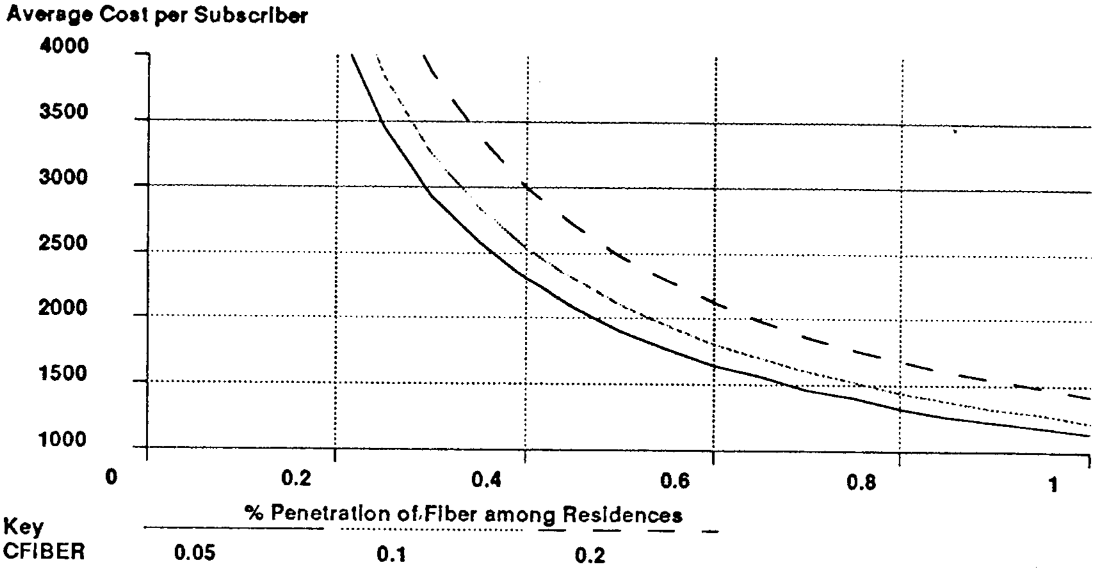
Several previous studies have suggested that capital costs must be in the range of $1000 - 2000 for a FORSN to be viable. These results suggest that this range can be achieved, but only if there is substantial penetration of the targeted neighborhood.

Some insight can be gained by examining the relative contribution from several components of the cost. Figure 4-2, calculated on the basis of 60% penetration, shows that the largest component by far is the distribution loop, followed by the RDU equipment costs. Active switching at the RDU dramatically reduces the need for feeder fibers, which thus contribute only a small portion to the total cost. CO costs include loop termination costs plus only those minimal investments in switching which go beyond what would be in place to supply N-ISDN service.

As noted earlier, distribution loop costs are sensitive to assumptions about population density. Figure 4-3 shows how distribution loop costs change if the lot sizes and typical block lengths are adjusted to correspond to 75, 100 and 150 houses per street mile.

At an estimated cost of $45 each, the wavelength division multiplexors used in the distribution loop are comparable in cost to running an extra fiber to each subscriber, at least for the lower values of fiber cost.

Figure 4-1: Average Cost per Subscriber for Active Double Star



However, given our assumption that fiber must be laid before the ultimate penetration is known, the use of WDMs substitutes a variable cost for a fixed cost. Thus, the savings is even more significant if penetration remains low (Figure 4-4).

4.1.1. On Demand Video

While most of the loop plant varies only with the number of subscribers, an increase in demand for unique video programs requires additional investment in the feeder plant and video switching. We have used our model to calculate the incremental capital cost per subscriber that would result from an increase of one erlang per subscriber in the average use of the network for on-demand video (Figure 4-5). An increase of one erlang in average weekly viewing implies 52 additional revenue generating hours per year to recover this capital cost. Thus an incremental capital cost of $50 can be recovered in three years through a charge of only $.33/hour for on-demand video service This cost is likely to be dwarfed by the cost of a video jukebox, and by royalty payments to program copyrightholders. [23] Viewed as an incremental cost above a base cost for a CATV-like service, on-demand video can be provided for a relatively low communications cost.

4.2. Switched Star

The active double star model employs electronics at the RDU in order to reduce dramatically the amount of fiber which must be installed by comparison with the single switched star. Equally importantly, in an environment of uncertain penetration, the active double star reduces fixed investment in fiber plant in favor of incremental investment in switching. Even at 100% penetration and a very low assumed cost for fiber, it appears that the double star is a superior solution (Figure 4-6).

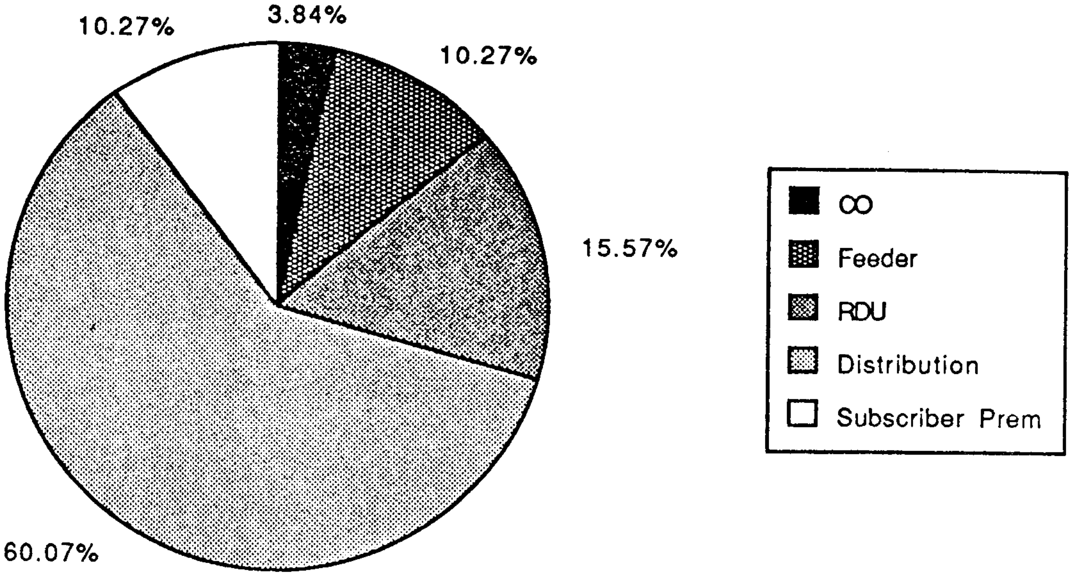


Figure 4-2: Total Cost Distribution at 60% Penetration

4.3. Passive Double Star

Hightower of BellSouth has proposed a passive double star architecture. Our analysis suggests that such an architecture does not offer substantial savings over other designs. Compared to the double star, the passive star uses more feeder fibers; in the distribution portion, installation costs dominate, and thus savings in fiber over the double star are less significant.

To be at all competitive with the double star, we must assume either a low bit rate for video, *e.g.* 45 Mbps, which is incompatible with future HDTV; or assume that by the time the demand for HDTV materializes, system capacity will have increased either through the use of coherent modulation and detection, or through the availability of low cost electro-optics and multiplexors operating at Gbps speeds, which allow a shift to 150 Mbps channels with no loss of capacity.

5. Conclusions

There are a number of conclusions we can draw from this preliminary analysis of fiber optic residential subscriber networks. First, it is clear that running fiber to the home, even assuming significant future reductions in component costs, is likely to remain more expensive than copper, where current loop plant

Figure 4-3: Average Distribution Loop Cost versus Penetration by Households per Mile

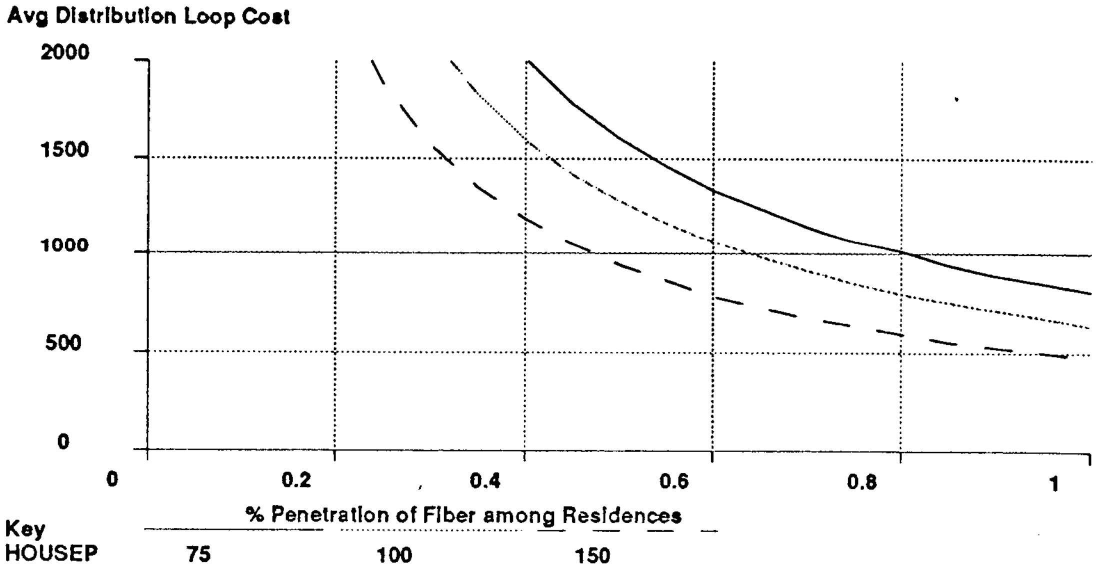
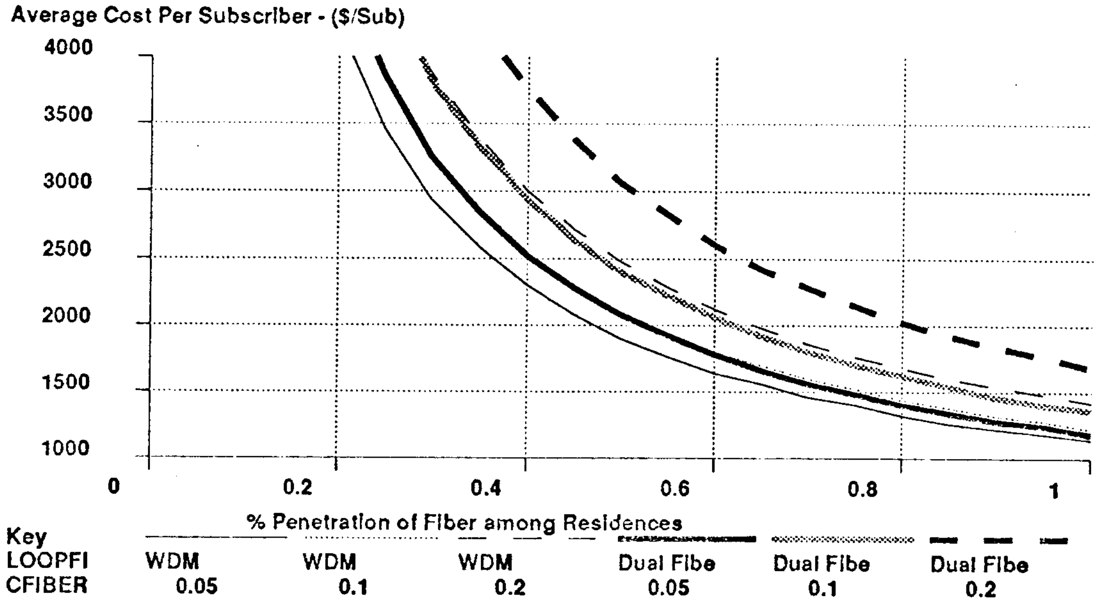


Figure 4-4: Total System Cost versus Penetration With WDM versus Dual Fibers



costs are roughly $700 per subscriber. [21] If we are to see the introduction of a FORSN, it must be justified on the basis of additional revenue producing services, such as the delivery of entertainment video.

Figure 4-5: Incremental Capital Costs for On-Demand Video

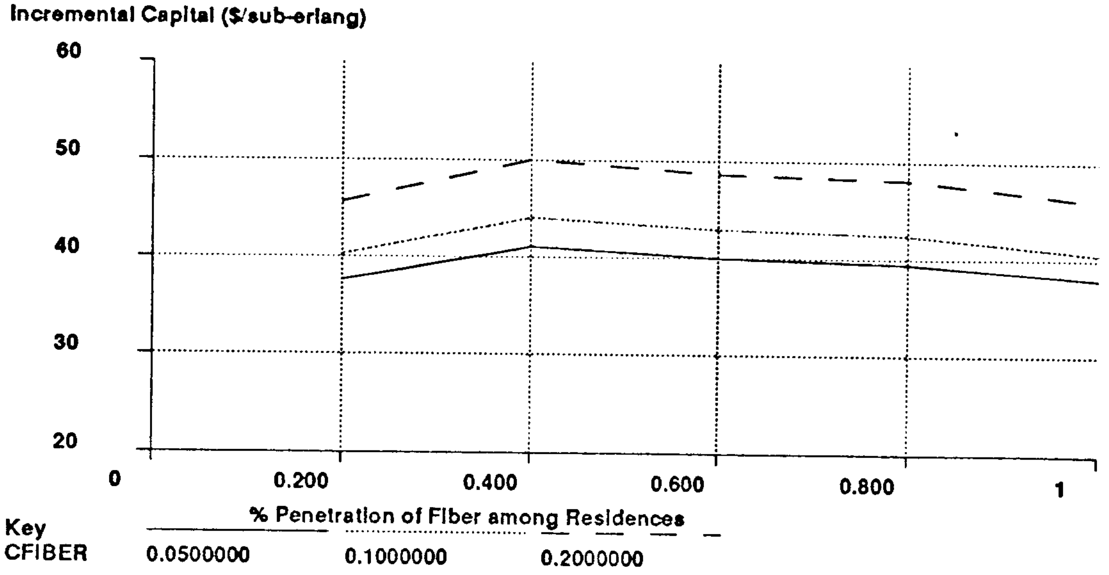
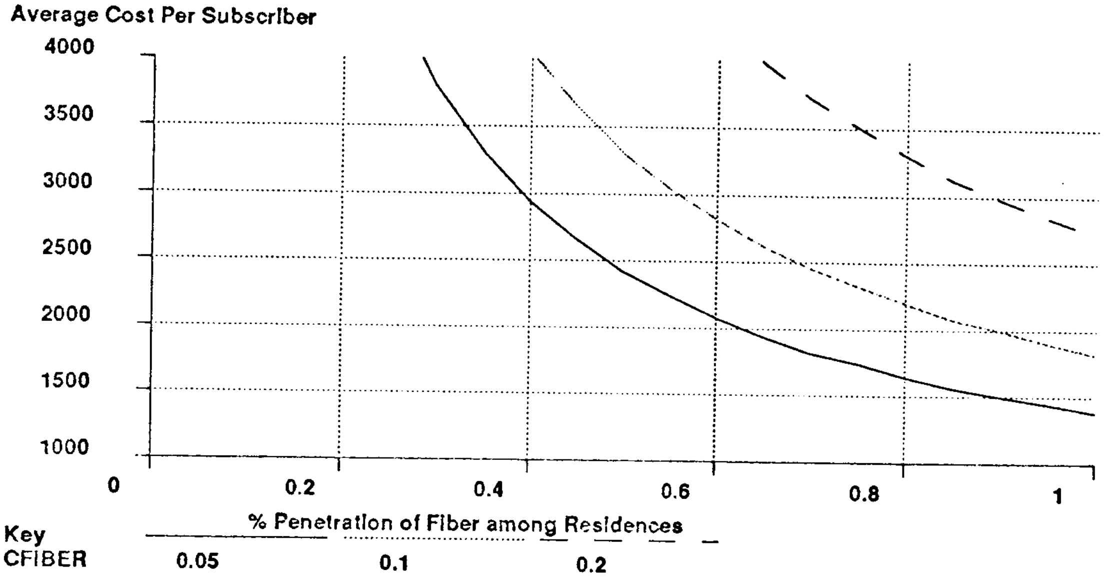
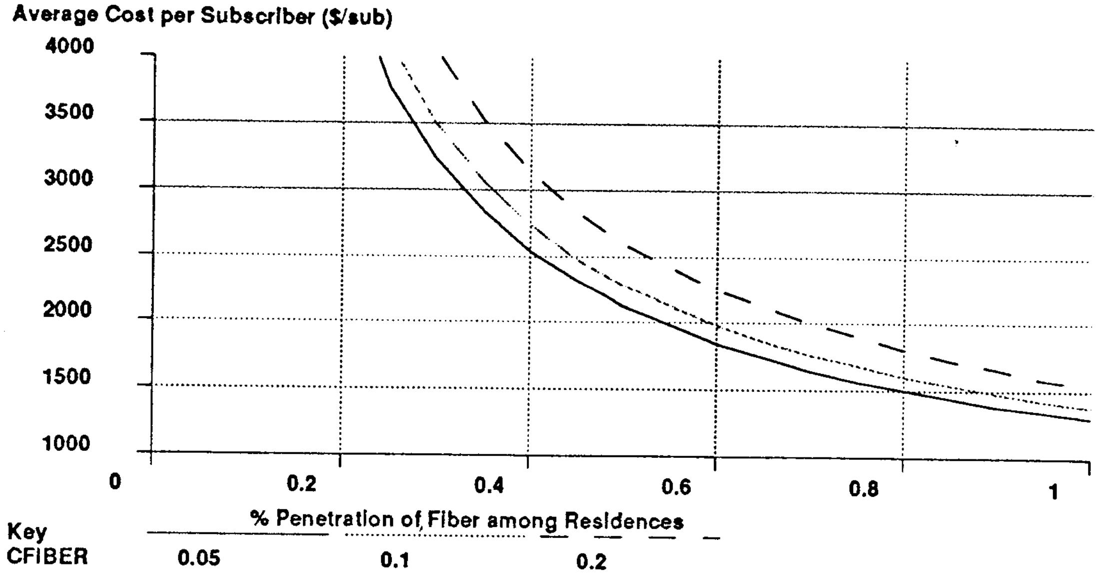


Figure 4-6: Average Cost Per Subscriber for Switched Star from CO



Point number one notwithstanding, our analysis suggests that a fiber optic network capable of providing both voice and video services to the home can be constructed for less than $1500-$2000 per subscriber. This brings it into the range of the combined cost of a CATV and telephone network, but

Figure 4-7: Average cost per subscriber for passive star using TDM



having far greater functionality.

Third, there exist a number of architectures which reduce the amount of fiber required in favor of remote electronics or optical equipment. To the extent that electronics costs can be reduced to the levels we project, such designs can significantly reduce the total cost of the loop plant. For example, in the active double star model, fiber costs account for less than 25% of total loop plant costs. Thus, we need not achieve fiber production costs greatly below those now attainable in order to realize an economical FORSN.

Fourth, the high installation costs for fiber argue for installing adequate capacity at the beginning to handle all subscribers in a serving area. Yet, it is unlikely that a FORSN, any more than CATV, will succeed in achieving 100% or even 70% penetration. In order to minimize the initial fixed capital investment, and the resultant economic risk that usage might not materialize at forecasted rates, it is desireable to select an architecture which trades fixed costs for equipment costs which are only incurred on an as-needed basis.

Fifth, the use of separate wavelengths to carry signals in both directions over a single fiber appears preferable to using dual fibers even under the most favorable assumptions regarding fiber cost.

Sixth, with respect to alternative architectures, some form of double star--whether passive or active--seems preferable to a single star on the basis of fiber cost savings. Other architectures, such as a bus, remain to be studied. It is still too early, given the rapid pace of development in electro-optics technoloyg, to determine a single optimum architecture.

With respect to the two double star desings, the cost of an architecture based on passive splitters is comparable to the active double star, which requires more untested electronics. However, pending the development of coherent modulation and detection techniques, or inexpensive components operating at Gbps speeds, the passive architecture we have modeled is limited to the carriage of NTSC as opposed to EQTV or HDTV signals. A judgement as to when support for the latter is required relative to when improved electro-optics will appear is needed to assess the importance of this limitation. None of our models include the equipment necessary for upstream video; however, a preliminary examination suggests that it will be far more difficult to upgrade a passive star architecture to support upstream video (*e.g.* for videotelephony) then to upgrade the single or double switched star configurations. Finally, the passive double star has a potential privacy problem since the signals for several households are carried on the fiber coming into each home. These signals are demultiplexed in the network circuit terminating equipment (NCTE) and only the signal destined for the particular home is passed to the codec. Security would be less of a problem, though by no means eliminated as an issue, if the NCTE could be treated as carrier rather than customer equipment, allowing the carrier to guarantee its integrity. Such a designation runs against current trends in FCC rulemaking. [14]

5.1. Policy Implications

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

If the success of a FORSN requires revenues from the carriage of entertainment video, then we can expect intense lobbying from the local exchange carriers (LECS) to ease the restrictions which currently restrict their entry into this market. [19] The FCC has already announced its intention to reconsider the cross-ownership rules which ban LECs from owning cable operations in their territory. Congressional action would likely be needed to relieve the constraints imposed by the Cable Act of 1984. We can also expect that the entry by the LECs into video carriage will raise again the question of whether video signal distributors should be treated as publishers or as common carriers. [34] On the one hand, the RBOCs have been lobbying heavily to have the MFJ's restrictions on content origination lifted so that they might participate more fully in the videotext marketplace. On the other hand, an RBOC freed from the need to separate carriage from content would be a much more threatening if it was then allowed to become the monopoly provider of wired video to the home. The RBOCs may well need to choose between government approval to become the monopoly supplier of wired video to the home, and freedom to originate content on their networks. They are unlikely to receive approval for both.

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

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

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

The LEC can better its chances for PUC approval by engaging the local CATV franchise in a joint venture. [5] A long term contract with a cable operator to provide video transport services over a FORSN shifts the subscriber penetration risk from the regulated PUC to the unregulated cable franchise. However, a FORSN threatens the cable operators's franchise monopoly, for it makes it possible for there to be many sources for video programming. Once a two-way switched video network is in place, any small businessman with a VCR and a few tapes can become a source for showing video on demand. Indeed, we may well see the development of the video equivalent of Computer Bulletin Board Systems: small scale providers of video information retrieval operated on a non-profit basis by individuals or clubs. Unlike the current voice switching systems, video switching systems will be designed from the beginning to replicate a single signal onto many lines, a necessary capability for the delivery of distributive video. Such a capability will enable every subscriber to become a potential broadcaster--limited only by the problems of identifying and marketing to an audience.

Finally, if the PUCs were to move from overall rate of return regulation to a price cap on basic voice service, then the risk of the investment in a FORSN can be shifted to the shareholders of the LEC. [29] Since revenue from POTS is capped, any losses which result from a failure to correctly guage the market for a FORSN cannot be passed on to the POTS ratepayer. By the same token, the LEC would then be in a position to reap fully the rewards of establishing a successful FORSN.

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

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