System and Cost Analyses of Broad-Band Fiber Loop Architectures

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***Abstract*—This paper presents analyses of four broad-band fiber-optic subscriber loop architectures, including active (high-speed TDM-based) and passive (dense WDM-based, dense WDM-based with an analog subcarrier-multiplexing overlay, and splitter-based) double-star topologies. The analyses focus on specific demonstrated architectures and use component cost projections based on learning curves to estimate future network costs on a per-subscriber basis. We find that the splitter-based passive loop can deliver voice and video services and that the dense WDM-based loop with a subcarrier-multiplexing overlay can deliver voice and broadcast video at lower near-term installed first costs than the other architectures. This is due to the sharing of bandwidth among a cluster of subscribers for the architectures that use splitters and to relatively lower costs for near-term analog subcarrier-multiplexed video delivery compared to digital video delivery. However, these cost disparities are smaller in the long term.**

We also investigate the sensitivity of projected cost per subscriber to remote multiplexing node size and to double-star prove-in distance. The results indicate that the four architectures have very different double-star prove-in distances and that passive loop costs are minimized for much smaller remote node sizes than active loops, thus permitting cost-effective deployment of passive loops for smaller groups of subscribers. In addition, cost breakdowns for the four architectures indicate that splitter-based passive loops share electronics more effectively among subscribers than loop architectures requiring dedicated (per-subscriber) electronic interfaces, resulting in projected cost advantages for the splitter-based networks.

I. Introduction

REPRESENTATIVE broad-band fiber loop networks proposed to date [1]–[7] have exhibited a wide variety of technological and architectural approaches. Differences among these alternative designs typically stem from differing assumptions on fundamental issues such as targeted time frame, service capabilities to be offered, technology availability, and relative technology costs. Although architectures optimized for current services such as plain old telephone service (POTS) and/or analog video distribution [4], [7] may have important near-term windows of opportunity, switched designs consistent with the future broad-band integrated services digital network (BISDN) ultimately should offer superior bandwidth, flexibility, and integration.

Optimum designs for future broad-band fiber loop architectures will depend on a host of technical and economic factors and no one specific design may be optimal in all circumstances. In today's copper-based loop plant, for example, subscribers near the central office (CO) normally are served by dedicated wire pairs while subscribers located beyond some critical distance from the CO are served by "pair-gain" (digital loop carrier) systems. Similarly, optical fiber loops may, in the future, serve subscribers near the CO with dedicated fibers and subscribers far from the CO with "fiber-gain" systems that conserve fiber. Fig. 1 depicts such a scenario. In this study, we refer to the boundary between subscribers served by dedicated fibers and those served by fiber-gain systems as the "single-star/double-star boundary," and we call the boundary radius R.

The so-called "double-star" topology has received wide support among those proposals designed for switched broad-band transport [8] as a way of achieving fiber gain in the feeder portion of the subscriber loop. As illustrated in Fig. 1, the double star consists of shared feeder fibers and dedicated distribution fibers which are joined at a remote node site. Signals destined for different subscribers are multiplexed together at the CO and transmitted downstream over the feeder to the remote node where they are demultiplexed onto the appropriate distribution fibers. Upstream transmission is similar, with signals from different subscribers multiplexed and/or concentrated at the remote node and sent over the feeder to the CO. The cost savings generated by this double-star approach relative to a single-star approach with dedicated fibers to each subscriber are significant for subscribers located far from the CO.

This paper estimates installed first costs per subscriber based on similar volumes of initial deployment for several alternative architectures, including active (high-speed TDM-based) and passive (dense WDM-based, dense WDM-based with an analog subcarrier-multiplexing overlay, and splitter-based) double-star topologies. We include all network components from the subscriber interface to the CO switch termination in the analyses. Key elements in the projected per-subscriber cost are identified. The level of technological maturity assumed for the components and subsystems used in our initial first-cost calculations corresponds to the mid-1990's. Extensions to the longer term are achieved by means of learning-curve cost projections.

System analyses of this type are critical for future network planning efforts because the successful introduction and penetration of any new technology (and the choice

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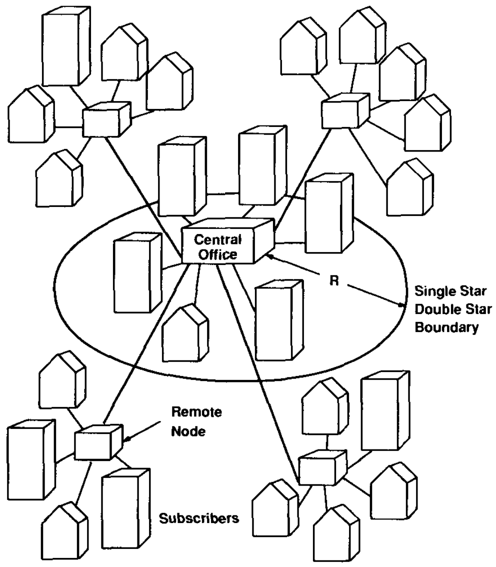

Fig. 1. Single-star and double-star topologies.

between alternative technologies) requires economic incentive and justification. Section II describes the four architectures studied in this paper. Section III details our baseline assumptions and models. Section IV discusses system optimization and cost sensitivities. Section V examines cost breakdowns, incremental service costs, and longer term cost projections. We summarize the main study conclusions in Section VI.

II. Alternative Architectures

The portion of the network considered in this study includes the following components and subsystems: optical network unit (ONU)[1] and other subscriber interface equipment; distribution plant, which includes service fibers, service access points, and distribution fibers; remote node equipment and controlled environment vaults (CEV's) when they are needed; feeder plant; and CO line interfaces. Service fibers connect subscriber interfaces to service access points where they are spliced to distribution fibers. Distribution fibers run between service access points and either remote nodes (for double-star subscribers) or CO's (for single-star subscribers). This section describes four broad-band double-star architectures for the fiber-optic subscriber loop. In all four cases we assume the same number of distribution and service fibers: namely, two dedicated fibers per subscriber (one upstream and one downstream) are used in each case to facilitate meaningful quantitative comparisons.

A. Active Double Star

The active double-star (ADS) architecture [1], shown in Fig. 2, features transmission over dedicated distribution fibers at rates of 155.52 Mb/s (the SONET STS-3

[1]ONU is a device at the end of the fiber, near the network interface(s) of the customer or customers subscribing to tariffed services(s).

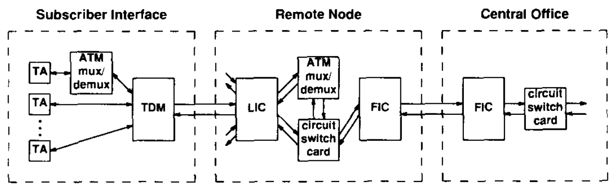

Fig. 2. Active double-star (ADS) architecture.

transmission rate) and 622.08 Mb/s (STS-12), a remote electronic node, and transmission over shared feeder fibers at 2.488 Gb/s (STS-48). The remote node contains equipment which performs high-speed time-division multiplexing (TDM) and traffic concentration and is housed in a controlled environmental vault with remote powering and air conditioning. This results in additional energy consumption compared to the single star and craft dispatch to handle maintenance and service churn.

The ONU for the ADS includes asynchronous transfer mode (ATM) multiplexers and demultiplexers which statistically multiplex voice, data, and signaling traffic, and TDM subsystems which perform time-division multiplexing between 155 and 622 Mb/s. Two different types of TDM are assumed: one performing 4 : 1 multiplexing bidirectionally and the other performing 4 : 1 multiplexing downstream only. The specific TDM configuration at different subscriber interfaces depends on service and traffic demands and varies among residential, small business, and large business subscribers. The ONU also contains optical transceivers, housings, and power supplies.

Distribution fibers in the ADS terminate at the remote node on line interface cards (LIC's), which contain optical transceivers and also multi/demultiplex between 622 and 155 Mb/s. ATM multiplexers and demultiplexers at the remote node statistically multiplex voice, data, and signaling traffic, while circuit-switch cards concentrate switched video traffic, provide feeder protection switching, and replicate broadcast signals. Finally, feeder interface cards (FIC's) perform TDM between 155 Mb/s and 2.488 Gb/s and optically transmit and receive feeder signals.

At the CO in the ADS architecture, there are again FIC's that transmit and receive optical signals and that perform TDM between 155 Mb/s and 2.488 Gb/s. Circuit-switch cards are used for feeder protection.

B. Passive Photonic Loop

An alternative to the active double star is the passive photonic loop (PPL) [6], illustrated in Fig. 3. The PPL uses dense wavelength-division multiplexing (WDM) between the remote node and the CO to provide fiber gain in the feeder plant and is representative of a broad class of new network architectures [9], [10] that process signals directly in the optical domain rather than via traditional, high-speed electronics.

Relative to the ADS, the LIC's, ATM multiplexers, and circuit-switch cards are transferred from the remote node to the CO in PPL, thereby eliminating CEV's, 2.488 Gb/s

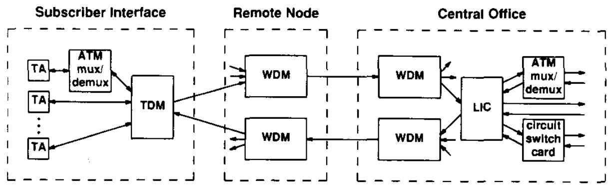

Fig. 3. Passive photonic loop (PPL) architecture.

feeder transmission systems, and powering requirements at the remote node. These changes should reduce remote maintenance requirements and should afford greater flexibility in installation and service provisioning.

In comparison to the ADS, a dense WDM network may require single-longitudinal-mode light sources, such as distributed-feedback (DFB) laser diodes, for transmitting broad-band signals. When narrow-linewidth lasers are multiplexed into closely spaced WDM channels, the emission wavelengths of the lasers must be stabilized to remain within their assigned bands. Since the emission wavelengths of DFB lasers vary with temperature, temperature stabilization of the laser packages is necessary. Commercially available DFB lasers are typically equipped with integral thermistors and cooling elements for this purpose, at some additional cost compared to conventional, uncooled laser diodes. The potential use of lower-cost multifrequency semiconductor lasers in multichannel WDM systems is discussed in [11], which reports the experimental feasibility of medium-density WDM.

The ONU in the PPL architecture studied in this paper is identical to the ONU for the ADS except that DFB lasers are assumed. The lasers transmit upstream signals on preassigned optical wavelengths. As for the ADS, the specific ONU configuration at different subscriber interfaces depends on the service and traffic demands of the different subscribers. The upstream signals from 16 subscribers arrive on dedicated distribution fibers at the remote node where a dense WDM device combines the wavelengths onto a single feeder fiber. At the CO, another WDM device demultiplexes them, and LIC's, ATM multiplexers, and circuit-switch cards perform similar functions to their counterparts in the ADS remote node.

In the downstream direction, high-speed electronic components again perform the same functions as in the ADS remote node. DFB lasers are assumed at the CO for downstream transmission, and a dense WDM device combines optical signals destined for 16 subscribers onto a single feeder fiber. Another dense WDM device at the remote node separates the signals and routes them onto dedicated distribution fibers.

C. Hybrid Passive Photonic Loop

Subcarrier multiplexing has been proposed as a near-term transport approach of broadcast video services [7]. In this technique, the baseband signals are used to modulate different electronic subcarrier frequencies which are then combined electronically, and the composite signal is used to modulate the output of a CO-based laser. At the subscriber interface, the optical signal is received and the electronic equipment recovers the desired baseband signals and routes them to the appropriate video terminals.

In the hybrid passive photonic loop (HPPL) [12] shown in Fig. 4, switched services are transported in a manner similar to transport on the PPL architecture, but broadcast services are transported via a subcarrier-multiplexing overlay. The HPPL model in this study also features the use of both power splitters and dense WDM devices to achieve a 16 : 1 fiber gain in the feeder plant, in contrast to PPL's use of two dense WDM devices.

Two-band WDM devices at the subscriber interface and at the CO in HPPL combine the upstream switched traffic and downstream broadcast traffic for both the distribution and the feeder. Optical power splitters at the remote node distribute the broadcast traffic and combine the upstream switched traffic from several subscribers. Dense WDM devices at the CO demultiplex the upstream switched traffic.

The transport of downstream switched traffic in HPPL is similar to that of upstream traffic, except that downstream switched traffic is not combined with broadcast traffic, and, therefore, does not pass through two-band WDM devices. Power splitters at the CO combine downstream switched traffic onto a shared feeder and, as in PPL, dense WDM devices at the remote node separate and route traffic to different subscribers on dedicated distribution fibers.

The analog nature of the broadcast traffic in HPPL affects the electronic and optical transceivers at both the CO and subscriber interface. The CO requires a subcarrier modulator for each offered broadcast channel, a subcarrier multiplexer, and an additional transmitter for every 16 subscribers. However, the LIC's, ATM multiplexers, and circuit-switch cards are simplified because they are no longer engineered for the broadcast traffic. At the subscriber interface, TDM multiplexers are similarly simplified, but a dedicated receiver for the broadcast traffic is required. In addition, demodulators and tuners at the subscriber interface recover baseband analog signals and select desired video channels. These replace the terminal adapters in an all-digital network (e.g., ADS and PPL) which are needed for framing and D/A conversion.

D. Passive Optical Network

Passive optical networks that rely on splitters rather than WDM devices have been proposed as an economical way to support the early deployment of fiber in the loop [4], [5]. In these networks, downstream traffic for several subscribers is broadcast by means of optical power splitters to several subscribers, and filters at or near the subscriber interface allow each subscriber to receive only the signals to which he or she is entitled. In the upstream direction, subscribers transmit at preassigned times so that their optical transmissions interleave. A ranging algorithm periodically measures transmission delays between the CO and each subscriber to synchronize the upstream transmissions.

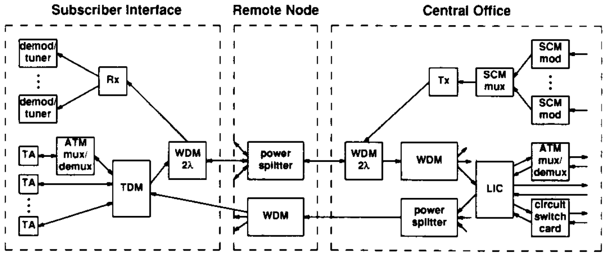

Fig. 4. Hybrid passive photonic loop (HPPL) architecture.

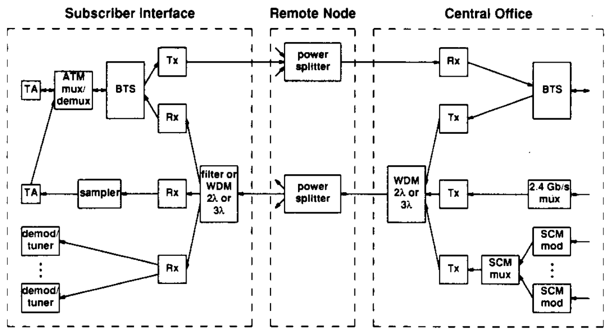

Fig. 5. Passive optical network (PON) architecture.

This paper studies one splitter-based loop architecture, shown in Fig. 5. This passive optical network architecture, which we refer to as PON, may be more limited than the ADS, PPL, and HPPL architectures with respect to services. In particular, the per-subscriber bandwidth in PON is limited to bidirectional digital traffic up to a few megabits per second, subcarrier-multiplexed broadcast traffic, and a single downstream switched video channel, in contrast to the ADS, PPL, and HPPL.

The ONU and the CO in the PON architecture include a bit transport system (BTS) which measures transmission delays as part of the ranging algorithm for synchronizing the upstream transmissions of multiple subscribers. They also include two-channel or three-channel (depending on the service demands) WDM devices to multiplex and demultiplex up to three downstream channels (ATM, subcarrier-multiplexed broadcast video, and switched video). The only component in the outside plant other than fiber is the power splitter, which both broadcasts downstream traffic to several subscribers (this paper assumes up to 16) and interleaves synchronized upstream traffic from different subscribers.

III. Models and Assumptions

A. Geographic Models

A model network of ten wire centers was used for this study. The model is based on an actual urban area and includes large business, small business, and residential subscribers. It includes one downtown CO, two nearby CO's with high business concentrations, and seven CO's serving mostly residential areas.

Loop models describing subscriber locations and fiber span lengths were defined for all architectures with 17 different remote node sizes ranging from 16 to 1024 subscribers. The remote node sizes of 16 and 1024 are based on the number of wavelengths that should be supported by readily available WDM devices in the mid-1990's and on expected CEV capacity [13], respectively. In addition, loop models were also defined for single-star areas serving any number of subscribers.

Subscribers in all loop models are uniformly distributed on 160′ × 160′ lots (0.6 acres). Remote nodes are located in the geographic centers of their serving areas and distribution fiber trenching is shared whenever possible. Feeder fiber trenching is shared for bundles of 384 subscribers in models with 384 or fewer subscribers per remote node and is dedicated to each remote node with more than 384 subscribers. In the single-star models, the CO is at the center of the serving area and trenching is highly shared.

B. Service Capabilities

This study assumes combinations of six different services [14] listed in Table I. POTS, data, conference video, and signaling information for all services are transported both upstream and downstream, while the video database, broadcast video, and video library services are transported only downstream. Usage for POTS, data, and conference video is based on today's statistics for comparable services, and residential video usage is based on today's usage of broadcast television.

In the baseline service scenario used in this study, large businesses have 250 POTS channels, ten data channels, one conference video channel, and four video database channels; small businesses have 25 POTS channels and ten data channels; and residential users have one POTS channel and can receive up to two broadcast video channels simultaneously.

C. Cost Estimation

This study used the same method to obtain the installed first cost per subscriber for all alternative architectures. Cost inputs for plant and equipment components were estimated on the basis of technology trends, research prototype experience, vendor products, and expert opinion. Ranges in both the input costs and their probable trends were also established. Actual costs for specific cases, however, could vary substantially due to installation conditions, variations in loop length, subscriber density, vendor prices, and other factors.

All equipment costs were established using a "bottom-up" approach [15]. That is, equipment was partitioned into functional groups which could be implemented in VLSI or highly integrated optoelectronic form. These were then combined into circuit boards and subsystems as described in [2]. The costs of assembly and packaging were considered together with those of the underlying materials. Common equipment, such as frames, power, and control, was also included in the estimates. A generic fac-

TABLE I
SERVICE MODELS

		POTS	data	conference video	video database	broadcast† video	switched video
bit rate	downstream	64 kb/s	1.5 Mb/s	155 Mb/s	155 Mb/s	155 Mb/s	155 Mb/s
	upstream	64 kb/s	1.5 Mb/s	155 Mb/s	64 kb/s	64 kb/s	64 kb/s
switching	downstream	packet	packet	circuit	circuit	circuit	circuit
	upstream	packet	packet	circuit	packet	packet	packet
large business	terminals/site	250	10	1	4	no service	no service
	daytime usage‡	5	5	5	12		
	nighttime usage	1	1	1	1		
small business	terminals/site	25	1	no service	no service	no service	no service
	daytime usage	5	5				
	nighttime usage	1	1				
residential	terminals/site	1	no service	no service	no service	2	1
	daytime usage	2.5				3	3
	nighttime usage	3.5				6	6

† Broadcast video has 64 offered channels.
‡ Usage in terms of peak hour CCS per terminal.

TABLE II
LEARNING CURVE SLOPES ASSUMED FOR DIFFERENT TYPES OF COMPONENTS

Component	Optimistic	Conservative
Electronics	73%	80%
Optoelectronics	73%	80%
Passive Components	80%	85%
Fiber Cable	75%	85%
Connector	80%	88%
Splicing	75%	85%
Enclosure	90%	95%
Trenching	100%	100%

tor of 1.4 was applied to each equipment component to account for installation and testing. This installation factor was kept constant over time.

A learning-curve method [16] was used to quantify the economies of scale that should be reflected in improved production techniques and lower costs as more production experience is gained and total production volume increases. All cost estimates assumed that the devices would be manufactured in sufficient volume (e.g., at least 10 000 units) to achieve volume production economies for the underlying technology. The values of the learning-curve slopes used for the different types of components, which express the fractional decrease in cost for every doubling of the cumulative volume, are shown in Table II. The average of the two extreme costs (optimistic and conservative) for each component is used in the following analyses.

For longer-term trends, the cumulative volume of plant and equipment components may increase at different rates due to other possible applications of the technologies. For simplicity, we distinguish fiber cable components from all other cost components because the initial cumulative volume for fiber cable is significantly larger—more than 2.1 million fiber miles have been deployed by local exchange carriers in the United States, principally in the interoffice plant [17].

IV. SYSTEM COMPARISONS

This section examines several system parameters, including the single-star/double-star boundary radius, remote node size, offer load of switched video, and passive multiplexing ratio for the four architectures described in Section II. We also discuss powering requirements and costs for the passive loop architectures compared to the active loop.

A. Boundary Radius and Remote Node Size

Figs. 6 and 7 present installed first costs per subscriber as functions of the boundary radius and remote node size, respectively, for each of the four architectures described in Section II. The costs presented in these figures are based on the service capabilities listed in Table I, excluding switched video. The figures show that the least-cost ADS network has about 800 subscribers per remote node and a boundary radius of 500 ft (we call this optimal boundary radius the double-star prove-in distance). Near the ADS cost minima shown in Figs. 6 and 7, network cost is relatively insensitive to boundary radius and remote node size. For boundary radii up to 8000 ft and remote node sizes from about 500 to 1000 subscribers, network cost per subscriber varies only within 1% of the minimum cost. In contrast, there are large cost variations for high single-star/double-star boundary radii and for low remote node sizes in the ADS. At boundary radii greater than about 8000 ft and at remote node size less than 500 subscribers, network cost increases from 1 to 100% above the minimum cost. ADS networks with high boundary radii or low remote node sizes, therefore, are unattractive from a first-cost viewpoint.

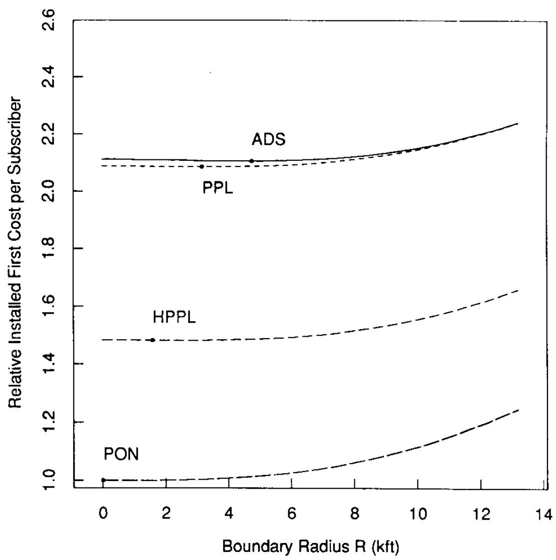

Fig. 6. Cost sensitivities to single-star/double-star boundary radii (dots denote minimum-cost point for each architecture). Services supported include POTS, data, business video, and broadcast residential video.

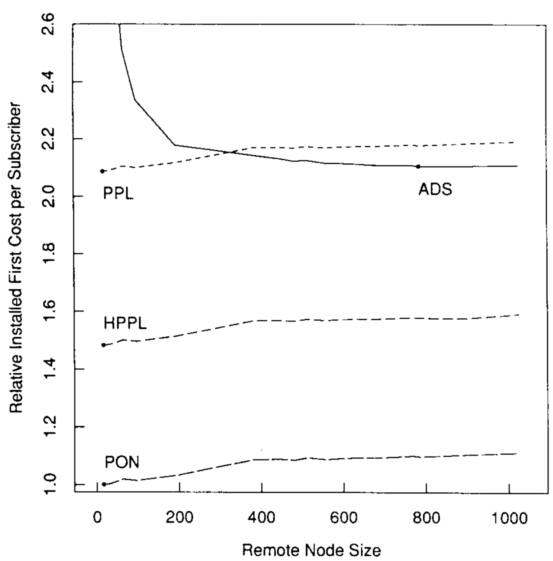

Fig. 7. Cost sensitivities to remote node sizes (dots denote minimum-cost point for each architecture). Services supported include POTS, data, business video, and broadcast residential video.

The PPL, HPPL, and PON architectures, also shown in Figs. 6 and 7, achieve their minimum costs at 16 subscribers per remote node and at boundary radii of 3200, 1600, and 0 ft, respectively. As in the ADS, network costs are relatively insensitive to boundary radius and remote node size around the minimum-cost point. For all three passive loop architectures, the costs of networks with boundary radii up to about 7000 ft and 200 subscribers per remote node are within 1% of their minimum costs. In these architectures, there are cost penalties for high boundary radii and, to a lesser extent, large remote nodes. These cost penalties, however, are less severe than in the ADS. This suggests that a greater array of passive network designs may be economically feasible.

The smaller remote nodes and boundary radii of the passive loop architectures suggest the following several possible advantages.

1) The smaller remote node would allow the passive loop architectures to be deployed cost-effectively for smaller pockets of demand.

2) The smaller optimal boundary radii in the passive loops should lead to a higher percentage of subscribers served by the passive loops, implying faster buildup of cumulative volume and more rapidly decreasing costs of the passive loop technologies.

3) The smaller remote node for the passive loops may have reliability advantages because component reliability requirements may be less exacting for the smaller failure-group sizes implied by smaller remote nodes.

B. Switched Video Offered Loads

This section analyzes the impact of peak-hour offered loads for switched video in two dimensions: installed first cost and fiber cross-section entering the CO. The latter dimension incorporates both feeder fiber from remote nodes and fiber from subscribers served by a single star. The analysis assumes a constant blocking probability of 0.01.

Fig. 8 shows fiber cross-sections averaged over the ten CO's in the model area. The results indicate that the ADS cross-section is sensitive to offered load while the cross-section in the three passive architectures is not. This is because feeder in the ADS is engineered based on subscriber usage while each of the passive architectures gives 16 subscribers at each remote node transparent 155 Mb/s video channels all the way from the CO.

The figure also indicates a crossover point for the ADS and PPL fiber cross-sections. This is due to the combination of TDM and traffic concentration in the ADS remote node which results in high fiber gain for the light offered load and in low fiber gain for the heavy offered load. In contrast, the fiber gain at the PPL remote nodes is achieved by WDM devices and is independent of the traffic.

Fig. 8 also shows that the fiber cross-sections in HPPL and PON are lower than those in either the ADS or the PPL. This occurs because the least-cost boundary radii are smaller in HPPL and PON, implying that more subscribers in these architectures are served by a double star and take advantage of fiber gain at remote nodes. Therefore, if fiber cross-section is an important concern in the outside plant because of congestion or limited space in available structures, networks can be designed with the smaller boundary radii that seem to be low cost for the HPPL or PON architectures.

Network cost trends in terms of the offered load of switched video are shown in Fig. 9 and are similar to fiber

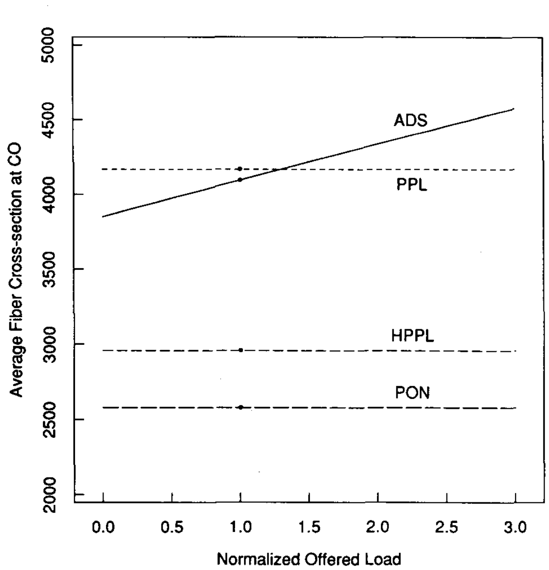

Fig. 8. Fiber cross-section sensitivities to switched video offered load (dots denote baseline usage assumption).

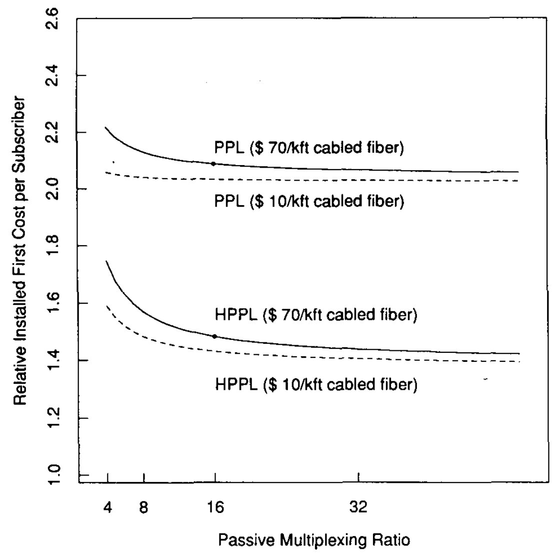

Fig. 10. Cost sensitivites to passive multiplexing ratio for PPL and HPPL architectures (dots denote baseline ratio at 16).

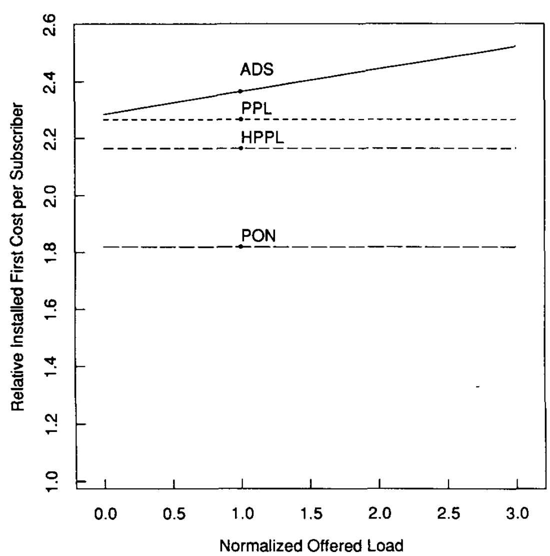

Fig. 9. Cost sensitivities to the switched video offered load (dots denote baseline usage assumption).

cross-sections. At a switched video offered load of three times the baseline assumptions, ADS cost increases about 7%. In contrast, passive loop costs for all three architectures are not sensitive to switched video offered load within the range of the traffic parameters studied here. This results from the fact that the three passive architectures provide dedicated video channels all the way from the CO to each subscriber.

C. Passive Multiplexing Ratios

Fig. 10 illustrates the costs of the PPL and HPPL architectures as a function of the passive multiplexing ratio, i.e., the number of channels per splitter and WDM device. The PON architecture is not included in this analysis because the PON splitting ratio directly affects the bandwidth per subscriber and, therefore, the transceiver speed and cost for each subscriber. The dots in Fig. 10 indicate our baseline assumption of 16 channels per splitter and WDM as well as $70/kft cabled fiber cost.

The data show that network cost increases only 2% for the PPL and 6% for the HPPL when we reduce the passive multiplexing ratios from 16 to 8. On the other hand, network cost decreases 1% for the PPL and 3% for the HPPL when we increase the ratios from 16 to 32. Thus, passive devices with as few as eight channels might be effectively used for loop network applications. This is significant because such devices are already available from several manufacturers.

If the cabled fiber cost declines to $10/kft (shown as dashed lines in Fig. 10), PPL cost increases by only 1% when the passive multiplexing ratio is reduced from 16 to 4. However, the HPPL cost increases by 11% if the passive multiplexing ratio changes from 16 to 4 due to less sharing of subcarrier multiplexing equipment at the CO. Thus, the cost increase observed when we decrease the passive multiplexing ratio all the way down to four depends on both the cost of the fiber and the extent to which such a change affects the sharing of other network elements.

D. Loop Powering

Powering is an important advantage of a passive loop compared to an active double star because the energy cost at the CO is lower than that at the remote node and because the passive loop consumes less energy overall than the ADS. To quantify this energy cost savings, we use the capital worth of a watt. The capital worth of a watt for remote locations is about \$20.00 [18], assuming the following [19]:

1) energy cost: \$0.10/kW · h,
2) energy cost increase: 4%/year,
3) federal income tax: 34%/year,
4) cost of capital: 12%/year,
5) cumulative discounted cash flow (CDCF) calculated for ten years,
6) performance coefficient of ventilation and air-conditioning system: 2.5,
7) AC-to-DC converter efficiency: 90%, and
8) DC-to-DC converter efficiency: 70%.

The capital equivalent of the energy cost saving of the passive loop relative to the ADS can be 30% per subscriber, assuming that the worth of a watt at the CO is \$19.00 [18], the ADS requires 6 W at the remote node and 1 W at the CO for each subscriber, and the passive loop requires 5 W at the CO.

V. Cost Comparisons

Based on the least-cost settings of some parameters studied in Section IV (boundary radius and remote node size) and on a nearly optimal setting for the passive multiplexing ratio, this section compares cost breakdowns, incremental service costs, and longer-term cost projections for the four architectures.

A. Cost Breakdowns

Fig. 11 shows the cost breakdown of the ADS, PPL, HPPL, and PON architectures (without switched video) in six categories: electronics, optoelectronics (i.e., optical transceivers), passive devices (absent in the ADS), distribution (including service access), feeder, and miscellaneous (housing, splices, connectors, and frames). Electronics is the largest component in each architecture, comprising 70, 65, 40, and 30% of the total costs of the ADS, PPL, HPPL, and PON architectures, respectively. It is worth noting that per-subscriber electronic costs are significantly lower for the HPPL and PON architectures because their optical power splitters permit more effective sharing of electronics by multiple subscribers. Electronic costs are greatest in the ADS, suggesting that cost reduction of electronic components would have the greatest impact on the ADS. On the other hand, optical transceiver and passive device costs are greater in PPL, HPPL, and PON, implying that continuing cost reductions for these technologies would favor the passive architectures.

In addition to these differences among the four double-star approaches, there are substantial fiber cost differences between the active and passive loop architectures. In the passive architectures, the absence of CEV's allows smaller remote nodes to be deployed closer to individual clusters of subscribers, decreasing distribution lengths. As a result, the costs of service fibers plus distribution in the passive loop architectures are about half that in the ADS. Feeder costs, on the other hand, are lower in the ADS because of the high fiber gain that results from the combination of TDM and traffic concentration. Altogether,

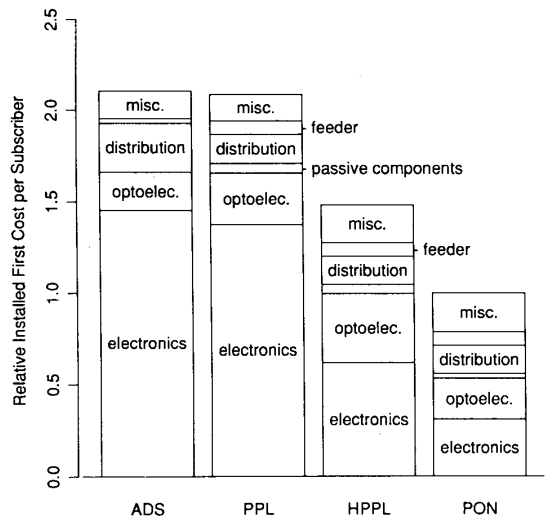

Fig. 11. Cost breakdowns. Services assumed: POTS, data, business video, and broadcast residential video.

however, the cost difference in distribution exceeds that of the feeder, and the fiber costs in the PPL, HPPL, and PON are less than fiber costs for the ADS.

B. Incremental Services

Fig. 12 presents the incremental costs for residential services in four loop architectures. POTS costs are comparable in the ADS, PPL, and HPPL architectures, while POTS in the PON architecture is about 60% of the cost. Broadcast video costs about 85% over the POTS costs for the ADS and PPL architectures but only about 30% for the HPPL. PON has a similar cost increment over POTS for broadcast video as does the HPPL architecture. Switched video, on the other hand, when added to POTS and broadcast video for residential subscribers, has much larger cost increments in the HPPL and PON loop networks than in ADS and PPL. This is because ADS and PPL infrastructures for broadcast video are capable of handling switched video with little change while HPPL and PON infrastructures require more extensive change to upgrade from broadcast to switched video. For networks with POTS, broadcast video, and switched video, Fig. 12 shows that a passive loop architecture may have as much as 20% first cost advantage over the ADS architecture.

C. Longer Term Cost Projections

In spite of nontrivial disparities among the initial costs for the four alternative architectures (without switched video), cost projections for the four appear to converge in the longer term. Fig. 13 plots these projections in terms of multiples of initial cumulative volume. The results predict that these costs will decline to the vicinity of \$1000 when the cumulative volume is about 1000 times the near-term volume (this occurs after ten doublings of initial volumes). The costs decline at composite learning curve slopes of 84–88% for the ADS, PPL, HPPL, and PON

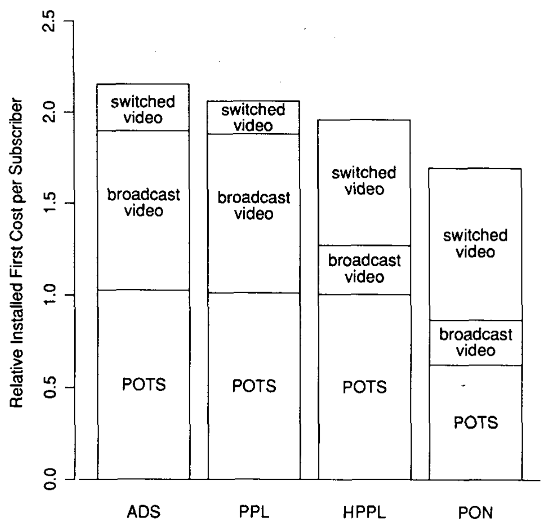

Fig. 12. Incremental residential service costs.

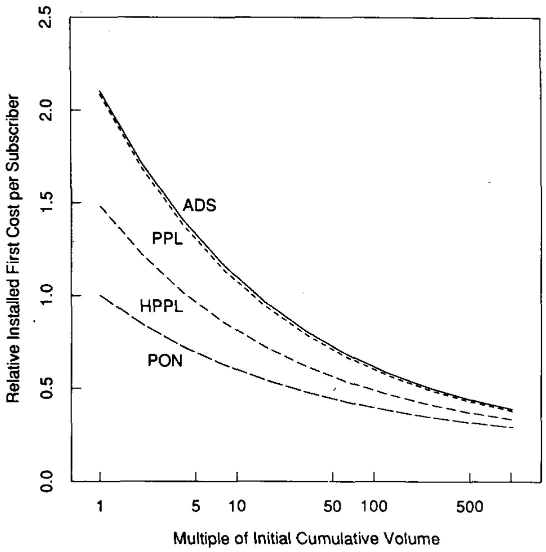

Fig. 13. Costs with respect to cumulative volume.

architectures. However, if these architectures follow different rates of deployment, and hence volume productions differ, their costs may not be as close as suggested by these results.

VI. Conclusions

With our current assumptions about component costs, installation costs, and learning curves, passive loop architectures that use optical power splitters or optical power splitters plus wavelength-division multiplexing components appear to have lower first costs per subscriber in the mid-1990's than the active double star or the passive loop that uses wavelength-division multiplexing only for fiber gain. In large cumulative volume, however, the installed first costs per subscriber for all four architectures considered here appear to be comparable. An important difference between the active and passive approaches is that these per-subscriber costs can be optimized at very different sizes of the remote multiplexing node: about 16 subscribers at the passive remote node compared to about 800 subscribers at the active remote node. Our analysis also suggests that eight-channel WDM components and power splitters, which are already commercially available from several manufacturers, may be cost-effective for PPL or HPPL architectures.

Comparing the active and passive architectures, we find in general that the passive loop architectures have lower electronics, fiber cable, and energy costs but higher optoelectronics costs. Lower distribution costs compensate for higher feeder costs for the passive loop architectures, since no CEV is required and the remote node can be deployed closer to subscribers. Moreover, an examination of the cost sensitivity to network service capabilities indicates that subcarrier multiplexing techniques and optical power splitters may be useful elements for implementation of passive loop architectures, because they significantly lower incremental costs to provide broadcast video (but not switched video). These technologies may be important ingredients in loop architectures that permit an early deployment of fiber in the loop for POTS and broadcast video. For loop architectures that use these technologies, future upgrades to and compatibility with emerging broad-band ISDN standards are important factors that are continuing to be investigated.

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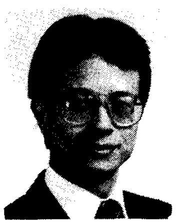

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