Fiber in the Loop

Peter P. Bohn
Michael J. Kania
Joseph M. Nemchik
Robert C. Purkey

The close of the 1980s saw many trials and applications of *fiber in the loop* or FITL. Most delivered traditional telephony (i.e., narrowband) services to the home, but a few provided both narrowband and entertainment video (i.e., broadband) services. During that time, the local-exchange carriers (LECs) also formulated their objectives and strategies for deploying FITL. As they gained a better understanding of the marketplace and the political realities of delivering video services, the LECs adopted an FITL-deployment strategy based on strict cost-effectiveness for the delivery of traditional telephone services. However, any fiber-optic access architecture they adopt has to support broadband services in the future. To address the cost and service challenges of FITL, the LECs and vendors must continually evaluate many alternative access architectures to identify potential advantages that can help fiber access achieve cost parity with copper access. Total system costs must be considered including electrical and optical components, powering system, fiber and cable components, and life-cycle costs (i.e., administration, maintenance, assignment, and provisioning operations).

Introduction

In recent years, the telecommunications industry has piqued its customers' interest with the promise of futuristic services that would revolutionize their lifestyles both at home and at the office. Simultaneous transmission of high-resolution video, digital audio, and data will open a new world of interactive services to users. One can envision such capabilities as electronic encyclopedias, shopping catalogs, travel and dining services, banking, and much more being brought to the home. Pay-per-listen services, with the ability to provide full-range audio and high-resolution video on demand, will make home entertainment an entirely new experience. Telemedicine and other video-imaging applications will allow better use of our most important resources (i.e., special experts such as a world-class heart surgeon) and improve the efficiency of our work force in general.

Critical to the realization of these services is the availability of a transmission medium to each user, a medium that has the necessary bandwidth capability. Arguably, copper pairs and coaxial cable can accomplish that task for several of these services. But as one envisions the broadband services expected over the next decade and beyond, fiber is generally accepted as the appropriate, longer term solution. Telecommunications providers recognize the opportunity these services offer to generate more revenue from their networks and are anxious to put in place the necessary fiber infrastructure.

Fiber Enters the Network. The existing loop portion of the network—i.e., the media that connect subscribers to the central office—consists predominantly of pairs of copper conductors. In 1982 when AT&T introduced the first fiber SLC® carrier system,[1] fiber started to provide the *feeder portion* of the loop (see Figure 1a). [The feeder is the part between the central office and the remote terminal (RT). The RT is usually located at a distribution point in the outside plant from which a particular geographic area of customers is served.] The use of fiber-

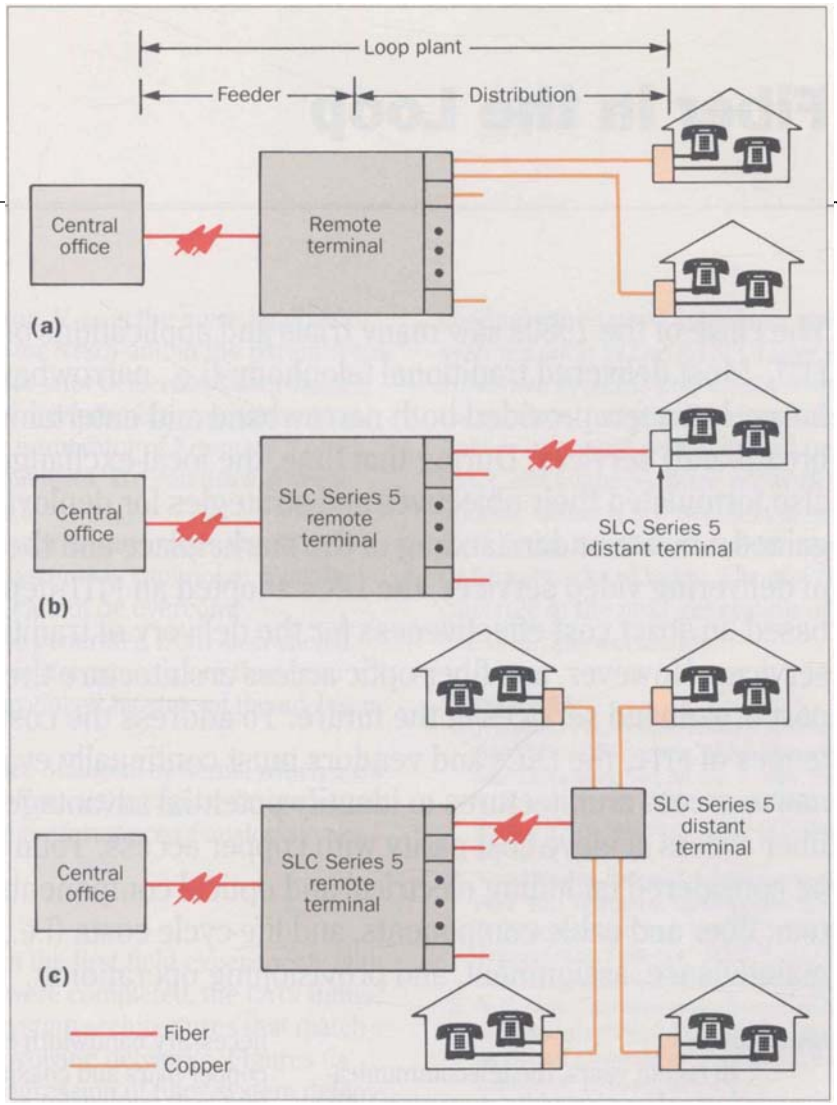

Figure 1. Evolution of fiber access in the loop. (a) The fiber SLC carrier system provided fiber in the feeder portion of the loop. Copper was still used in the distribution portion. (b) Initially, the fiber-to-the-home feature of the SLC Series 5 carrier system added fiber to the distribution portion of the loop, but each home required a separate distant terminal. (c) With fiber to the curb, a cluster of homes may be fed from a single distant terminal.

based feeder has been a quickly growing trend in recent years, and is now a widely accepted practice in the industry. However, the *distribution portion* of the loop (i.e., the part between the remote terminal and the subscribers) has remained all copper. (Panel 1 defines acronyms and terms used in this paper.)

AT&T recognized the need for an infrastructure with greater bandwidth capability to each subscriber and, in 1988, introduced the first *fiber-to-the-home* (FTTH) system. The system (see Figure 1b) used existing SLC® Series 5 equipment over several high-speed fiber links between the central office and remote terminal. For the remote terminal, AT&T had developed special channel units and optical cards that allow two or four DS0 channels to be transmitted over a single fiber to a *distant terminal* (DT) mounted on the side of a subscriber's home. At the distant terminal, the optical signals were converted to electrical signals and demultiplexed.

Conventional copper drop wires were then run from the distant terminal into the home. Each distant terminal had the necessary power conversion equipment, ringing generator, and batteries. This architecture provided POTS (plain old telephone service) to subscribers over a nearly all-fiber loop.

FITL Deployment. Most trials and early applications were concerned with the delivery of traditional narrowband service to the home, i.e., POTS. However, a few trials were designed to show that the LECs could deliver both narrowband and entertainment video services to the home. In general, this was a period of experimentation as several LECs deployed systems from several vendors who used different approaches for fiber access.

This was also the time when the LECs defined their FITL objectives and formed strategies for FITL deployments. They began to understand the marketplace and the political realities of their entry into the delivery of video services. Strict cost-effectiveness became their FITL deployment strategy for POTS delivery. However, they expected future opportunities that would require fiber access to support and carry broadband service—in particular, community-antenna television (CATV) in the near term, and broadband integrated services digital

Panel 1. Abbreviations, Acronyms, and Terms

AM — amplitude modulated
BISDN — broadband integrated services digital network
CATV — community-antenna television; cable television is the most prevalent form
distribution — portion of the loop between the remote terminal and the subscribers
DLC — digital loop carrier
DS0 — digital signal level 0; a transmission rate of 64 kb/s (one channel) in the time-division-multiplexing hierarchy
DT — distant terminal
EMI — electromagnetic interference
FDM — frequency-division multiplexing
feeder — the portion of the loop between the central office and the remote terminal
FITL — fiber in the loop
FTTC — fiber to the curb
FTTH — fiber to the home
IFC — installed first cost
InGaAsP — indium gallium arsenide phosphide
InP-InGaAs — layered indium phosphide and indium gallium arsenide
LEC — local-exchange carriers
LED — light-emitting diode
loop — the media that connect subscribers to the central office
LU — living unit
MLT-LMOS — loop-maintenance operations system for mechanized loop testing
MSDT — multiservices distant terminal
OAM&P — operations, administration, maintenance, and provisioning
PIN — positive-intrinsic-negative
PON — passive optical network
POTS — plain old telephone service
OILU — optical interface unit
RT — remote terminal; located at a distribution point in the outside plant from which a particular geographic area of customers is served
tapered fiber — diameter of the optical fiber increases (or decreases) with distance along the fiber's optical axis
SIR — signal-to-interference ratio
TV — television
UHF — ultra high frequency
VCR — video-cassette recorder
VHF — very high frequency
VSB-AM — vestigial sideband, amplitude modulated
WDM — wavelength-division multiplexer

network (BISDN) in the long term. (Cable television is probably the most widely known form of CATV and is often used as the meaning of this acronym.)

In this paper, we discuss the issues identified in the FITL trials, and the economics of fiber access versus copper access. We also briefly describe alternative architectures for an FITL system, and discuss the roles of standards and standard interfaces. Finally, we describe the technologies used in AT&T's FITL system.

Field Trials and Issues

The LECs were extremely interested in examining the FTTH concept and have conducted field trials over the last few years. While other telecommunications suppliers have introduced FTTH systems, most of the field trials in the United States used AT&T equipment. These trials encompassed a diverse group of Regional Bell Operating Companies and independent LECs, and involved a wide cross-section of geographic locations.

The AT&T trials, which focussed on the delivery of traditional narrowband telephone service, were considered so successful that all these systems are still in service and there are no plans to replace them. Our system met both AT&T's and our customers' expectations for installation, network performance, and hardware reliability. However, these trials identified several issues that must be solved before fiber can be deployed ubiquitously in the loop:

- Cost of fiber loops versus copper loops
- Powering arrangements for distant terminals
- Operations, administration, maintenance, and provisioning (OAM&P) procedures.

Cost Parity with Copper. The first issue that faces the FITL concept is to achieve life-cycle cost parity with

copper loops. (*Life-cycle cost* refers to all the expenditures associated with a system's period of deployment; i.e., installation, cost of equipment, operating costs, maintenance, capital depreciation, and replacement of worn-out items such as batteries.)

Because the services available today do not mandate the installation of fiber in the loop, the LECs have based their FITL deployment strategy on strict, cost-effective delivery of traditional telephone services. The trial activity confirms that this will be an imposing target.

The high initial costs of fiber, active optical devices, and related electronics suggest that the FTTH architecture cannot show cost parity in the near term with low-cost, conventional copper-access alternatives.

Powering the DTs. The second issue is how to supply power reliably and efficiently to the distant terminals. Copper distribution plant does not require remote powering. But if electronics and optics are placed near the homes, these components do require a remote power source. In addition, all applications require backup power arrangements, e.g., batteries, which are used when normal power is not available. (We will return to this powering issue shortly.)

OAM&P Procedures. A third major issue is to establish efficient operations, administration, and maintenance procedures for FITL applications. To offset the first-cost penalties associated with FITL systems, the LECs are relying on the life-cycle cost benefits of a fiber loop. This means that the cost of administration, maintenance, and assignment operations must be reduced, compared to this cost with the copper alternative. (See Appendix A.)

FITL systems need to be designed with built-in maintenance, testing, and monitoring capabilities that must be compatible with the LECs' existing methods, procedures, and operations support systems.

Interrelated Solution. Because these issues are interrelated, they cannot be solved individually. As the LECs try to move from the trial phase to the deployment phase, the need for immediate, cost-effective FITL solutions has become the overriding consideration. A formidable challenge for system designers will be to solve these issues while increasing the overall reliability of the loop.

Economics

The Public Utility Commissions will closely scrutinize the use of FITL technology and require that the LECs justify the cost of this technology economically versus that of traditional copper alternatives.

Toward that end, the FTTH architecture described earlier has evolved to a *fiber-to-the-curb* (FTTC) concept (see Figure 1c). While the FTTH configuration is compelling because of its simplicity and maximum fiber penetration, the placement of active electronics and optics on each house cannot be justified economically. The need to share these costs has driven the LECs to relocate the distant terminal to curbside, where common costs can be spread among several customers. Copper drops are run from the distant terminal to each subscriber's home; standard distant-terminal equipment readily accommodates distances up to 1300 feet.

The hybrid, fiber and copper distribution portion of the loop should be adequate for near-term services. However, each FITL vendor is developing an evolution strategy to use fiber all the way to the home to provide BISDN service in the longer term.

In response to the need for an FTTC vehicle, AT&T has developed its second-generation FITL system. The new SLC–2000® multiservices distant terminal (MSDT) will operate initially with a SLC Series 5 remote terminal but is designed to be compatible with the upcoming SLC–2000 access system. The MSDT can provide up to 24 DS0 channels, which are transported from the remote terminal over a single, bidirectional fiber link. Unlike the earlier FTTH system, the MSDT provides a full-range of POTS and special services for residential and small-business customers.

Increased sharing of electronics is the near-term key to FITL economics. When the MSDT is deployed at the higher sharing levels it permits, its cost allows the LECs to meet their FITL cost objectives. The LEC cost targets are based on comparisons to copper alternatives. To develop these targets, one generally uses a model for the costs of installing the distribution portion of the entire loop. Any preconditioning for future services—such as installing more than one fiber per distant terminal, or placing wavelength-division multiplexers (WDM) for future transport of simultaneous signals on a common fiber—will lower the remaining cost targets for the active electronics.

The challenge here is to develop a scheme to upgrade a network from POTS to BISDN service, yet use the smallest number of fibers per distant terminal. Plans for services beyond telephony, and perhaps cable television, must be adjusted regularly until a demand for such

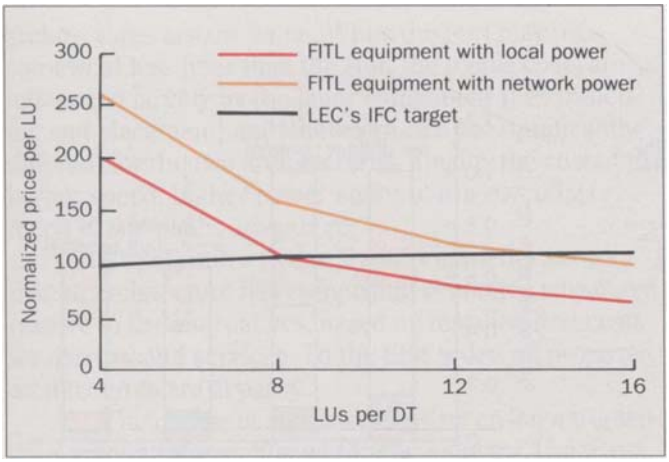

Figure 2. Fiber-in-the-loop (FITL) price targets. Most installed-first-cost (IFC) targets can be met when a distant terminal (DT) serves 8 to 16 living units (LUs). Because power to the distant terminals comes from a central point (e.g., the remote terminal), the network-powering scheme needs fewer battery sites than the local-power approach but requires a copper distribution network.

services exists in the residential environment.

The number of living units (LUs) that a distant terminal serves depends on the:

- LEC's cost targets
- Topology of the particular area to be served
- Planning and engineering practices used by the LEC.

As one can see from the typical installed-first-cost (IFC) target and FITL prices in Figure 2, most LEC cost targets can be met when a distant terminal serves 8 to 16 living units. To be effectively deployed in this environment (i.e., meet the LEC's FITL cost targets), distant terminals must be able to serve 24 or more lines.

Powering the Fiber Loop

As we stated earlier, the second FITL issue to be addressed is that of developing practical and affordable powering arrangements. Recent natural disasters—such as the California earthquakes in San Francisco in 1989 and Los Angeles in 1990, and Hurricane Hugo in the Southeast in 1990—have emphasized the need of the telephone network to operate for extended periods when commercial power has been lost. Disasters have also brought into question the powering architecture and requirements for fiber systems.

The requirements for the early FTTH systems specified that the distant terminals be powered from an ac (alternating current) source provided by the electric utility and have up to 8 hours of battery reserve. However, the FTTH trials pointed out that coordination between the LECs and the electric utilities could be an administrative problem.

At the request of some customers, AT&T developed an alternative arrangement that obtained power directly from the customer's premises. In this approach, a low-voltage dc (direct current) power supply was installed on the outside wall of each house by the LEC craftsperson. Although this local-power alternative eliminates the coordination issue with commercial power, concerns remain about the performance, reserve time, life expectancy, monitoring, and replacement of the multitude of batteries.

Operation during long-term power failures is impractical with both the commercial- and local-power arrangements.

The move to an FTTC concept enables the LECs to consider a third power alternative, i.e., network powering. Here, –130V (volts) of dc power would be provided to each distant terminal from a centralized point owned by the LEC. This scheme would centralize batteries at one location (perhaps, at the remote terminal), which eliminates their need at each distant terminal. In addition, network powering permits easier servicing and allows a motor generator to be used in emergencies. However, some copper is required from the central power point to each distant terminal to supply the power.

Figure 2 compares price curves for FITL equipment with local power and with network power. (See Appendix B for further discussion of the powering issue.)

Alternative Architectures

The need to reduce the cost per living unit of FITL systems has prompted an aggressive search among alternative fiber-access architectures as a possible way to moderate the high costs of new optical technologies.

The AT&T offering currently uses a technique known as the *active star* architecture (Figure 3a). In this arrangement, certain network-management functions (such as switch interfaces and bandwidth management) and high-speed multiplexing are done at the remote node (or the remote terminal in AT&T's system). Individual low bit-rate [i.e., 1.5 Mb/s (megabits per second)], low-

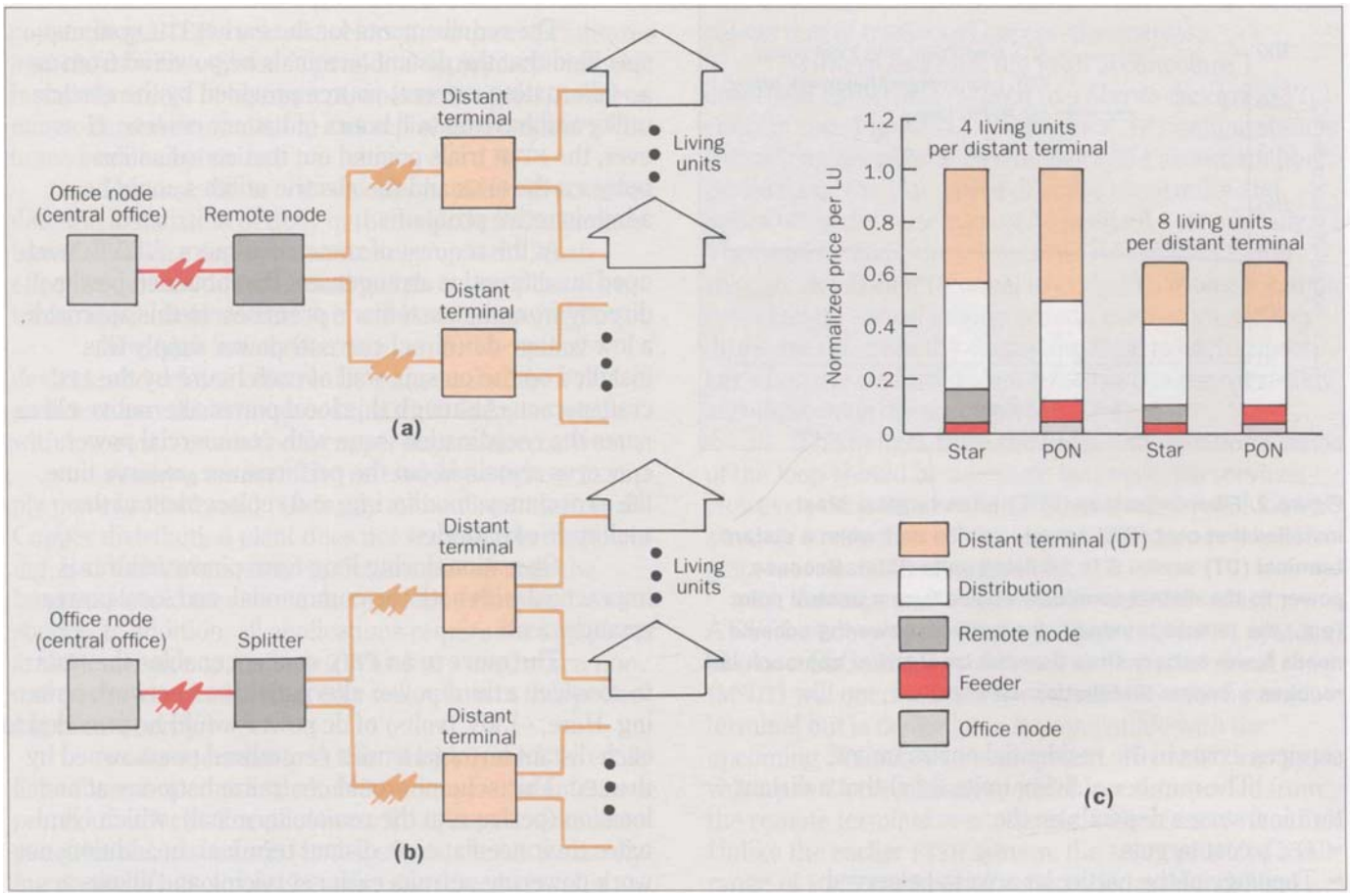

Figure 3. Architectural alternatives for FITL access. (a) In the star configuration, network management and high-speed multiplexing occur at the remote node, i.e., the remote terminal in AT&T's current system. Individual low-bit-rate (i.e., 1.5 Mb/s), low-loss links are established between the node and each distant terminal. (b) In the passive optical network or PON, the network-management functions are done at an office node (or central office in the AT&T terminology). From there, a high bit-rate (i.e., 20 Mb/s) link is established to a point near the distant terminals. Several distant terminals share the cost of the optics, and fewer fibers are used. (c) Analysis of the installed first costs of two alternatives for narrowband services shows that neither architecture offers an economic advantage. However, increased sharing improves the economics of both alternatives.

loss links are established between the remote node and each distant terminal.

Another alternative, the *passive optical network* (PON) architecture in Figure 3b, is based on the principle of sharing the cost of the optics across several distant terminals and reducing the total number of fibers used. In a PON arrangement, the network-management functions are moved back to an office node (or the central office in AT&T terminology). From this point, a high bit-rate (i.e., 20 Mb/s) link is established to a point near the distant terminals.

Conceptually, the PON arrangement would appear to provide a significant cost benefit. But when one does a comprehensive comparison of the economics of the two architectures, that is not the case.

Three components—the distant terminal, power, and media—dominate the cost of the FITL systems. The distant-terminal and power costs for the two

architectures are the same. While the PON may use somewhat less fiber than the star, the media costs are influenced largely by the labor component (i.e., trenching and placement) and, therefore, are not significantly different for the two architectures. Finally, the cost of the higher speed, higher power optics of the PON offsets much of any media advantage.

A comprehensive analysis (Figure 3c) shows that no architecture has compelling economic advantage relative to the alternatives, based on installed first costs for narrowband services. To the first order, all proposed architectures are at parity.

The choice of architecture is receiving a tremendous amount of attention within the industry. Unfortunately, those discussions often cloud the real issues, which are independent of architecture. As the analysis shows, it is increased sharing of distant terminals that has the major impact on cost with both of these alternatives. While distant-terminal costs may moderate over time, any wide-scale deployment for the next 5 to 10 years must be made based on an FTTC approach. The sharing of distant-terminal costs over 8 to 16 living units allows FITL systems to satisfy LEC cost targets.

Standards and Standard Interfaces

Several design parameters define the voice-frequency transmission performance of a loop transmission system. For DLC terminals, these parameters are carefully defined and specified in Bellcore's TR57.[2] (DLC stands for *digital loop carrier*, e.g., the SLC Series 5 carrier.) During the development of the initial FITL system and from field-deployment experiences, it became clear that there are significant differences between a typical DLC system and an FITL system.

If the only consideration were the operation of simple telephone sets, then the battery supply could be as low as 10V. This would be desirable from a powering viewpoint, but there are reasons that preclude the use of a low-voltage feed:

- Answering machines have a 21V threshold that is used to detect on off-hook on the line, i.e., someone lifted the handset to begin a call. (This threshold is specified by T1C1, the committee of the American National Standards Institute that sets standards for customer-premises equipment.)
- Maintenance termination units, which are test isolators used by many companies, have a nominal 36V breakdown threshold.
- We are dealing with a large embedded base of loop terminal products designed to expect that a 48V battery circuit would be used to feed the loop.

For many cases (e.g., microphone requirements and Touch-Tone dialing), the use of a lower voltage is not a problem. Set designers will probably continue to assume a 48V feed. However, until a specific standard exists that describes a low-voltage interface, it is prudent for channel-unit circuits to have a minimum open-circuit voltage of 42.5V, the voltage that corresponds to DLC and central-office channel units.

Telephone dialers are required to operate with loop currents as low as 18 mA (milliamperes). Again, from a power-consumption viewpoint, it would be desirable to operate at this current. There is a fundamental reason to set the value of loop current higher: Telephone sets are normally designed with loop-length compensators that increase the gain on long loops by sensing the loop current. Although we could cancel this effect by increasing channel-unit loss, the compensators cannot completely make up for the progressively reduced and uncharacterized efficiency of carbon microphones below 30 mA. To compensate for the increased gain, we could, in principle, precisely adjust the gain in each direction. However, the symmetry requirement (i.e., TR57) and the uncharacterized nature of microphone performance call for a minimum loop current of 30 mA.

Most loop-transmission plans specify a channel-terminal impedance of 900 ohms in series with 2.16 microfarads. This value is a compromise based on a best, composite grade of service for all customers within the service area of the system. Customers located close to the channel circuit or at the end of the serving range receive poorer transmission performance than those near the center of the serving range. All customers on an FITL system are connected with a zero-loss loop. Hence, a more appropriate terminal impedance is 600 ohms, i.e., the nominal impedance of the telephone set alone.

Transmission plans for loops also specify a nominal loss based on a compromise grade of service. When telephone sets are connected directly to central-office or DLC channel units, users generally rated a call's sound quality as *too loud*. Our studies show that, to compensate for the zero-loss loop, 3 dB (decibels) of added loss in both directions is required at a loop current of 30 mA. As an added benefit, this extra loss reduces idle-channel

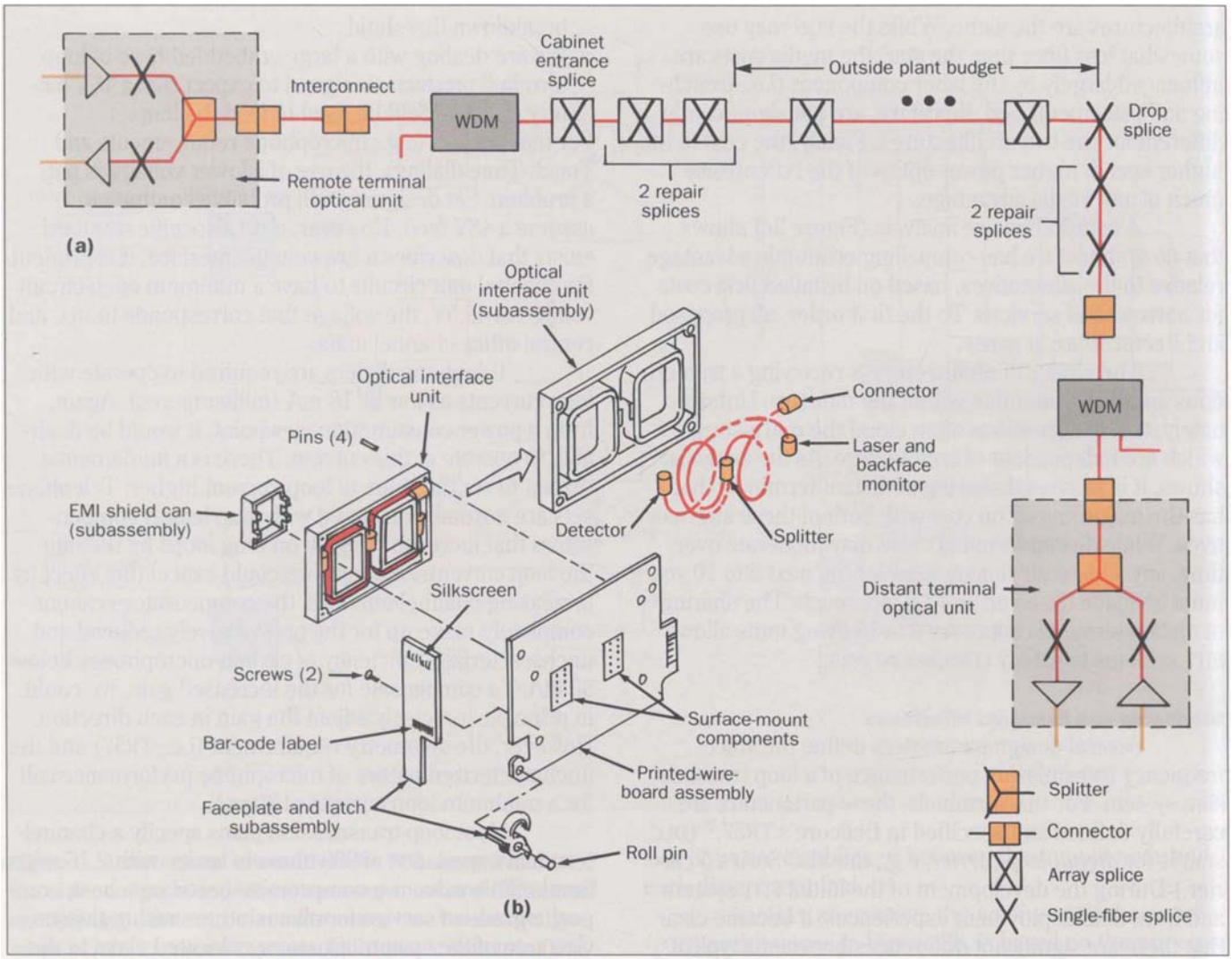

Figure 4. The SLC Series 5 carrier system's fiber-to-the-home feature. (a) The link model for the system had an outside-plant loss requirement of 8.2 dB, which includes some margin for repair splices. For a two-fiber, analog AM video and narrowband system (video is on the second fiber), the video transmission parameters limit outside plant loss, which then exactly meets Bellcore's requirements. (b) At the remote terminal and distant terminal, an optical interface unit serves as the interface to the optical media.

noise (i.e., the residual "hiss" present when neither party is talking). Callers are usually pleased by the "clear, quiet sound" produced with these parameters. The return-loss requirements of TR57 must be met but must be measured with a 600-ohm termination to account for the new channel-unit impedance.

Because the very short loops of the FITL have minimal exposure to surges and crosses when compared with normal loops, one might conclude that a less robust protection circuit could be used. (*Robust* refers to the circuit's ability to tolerate repeated stress.) The possible consequences of lightning-induced surges and power crosses are so serious that we believe the protection

requirements should not be compromised at all.

FITL loops also have greatly reduced exposure to longitudinal interference. Therefore, the longitudinal balance requirement can be reduced from 60 dB to 40 dB or less. Also, the requirement to accept a longitudinal interfering current without distorting the signal can be greatly reduced.

The size of the local ringing generator in an FITL system can take into account the reduced loop loss. But like any DLC system, the FITL system must allow for five ringers on each line and cannot make assumptions about coincidence on different lines. Thus, these systems can reduce the ringing voltage to 70 Vac (volts alternating current) and still maintain full service capability. The provision of ringing voltage is, perhaps, the most onerous of the powering issues for loop-fiber systems.

To isolate a problem, designers of loop-testing systems go to great lengths to model and measure the electrical characteristics of a questionable circuit with high accuracy. The long loop is the source of many of the measuring difficulties. When a very short drop is used, one can ignore the effects of longitudinal interference. The masking effect of the loop resistance on ringer detection and receiver off-hook detection is removed, and it is possible to design a cost-effective test module that can be used in each terminal.

These findings are being incorporated into the next generation of FITL systems and have provided input to Bellcore's new standard, TA–NWT–00909.[3]

Optical Technologies and Architecture

Before the FITL system was developed, several decisions about the general system design were necessary, including:

- Choice of fiber type (i.e., single mode versus multimode)
- Optical device technologies to be used
- General transmission architecture.

Although we discuss them sequentially here, these topics obviously are interrelated and decision making was a feedback process.

Optical Medium. In some respect, the type of optical medium was an easy choice. Our customers dictated that we use single-mode fiber. The reason for this was clear: The entire purpose of installing a fiber-optic infrastructure was to be ready to transport future services to subscribers. Because many of these are likely to be wide bandwidth services, the use of multimode fiber could present a bandwidth bottleneck to service evolution.

Clearly, there were some economic benefits to the use of multimode fiber. In 1987 when AT&T's FITL system was initially designed, multimode splices and connectors were less expensive than their single-mode equivalents. Also, the time required to make multimode splices in the field was shorter and, therefore, they were less expensive than single-mode splices. However, it was also clear at the time that learning-curve effects would bring the two technologies to equality within a short time. This has since proved to be true.

One of the more difficult decisions made was about the number of fibers per distant terminal to be used only for narrowband services. Because these services are bidirectional, we had two choices:

- Use two fibers to obtain bidirectionality, as in most optical telecommunications systems.
- Use one fiber and some form of optical or electronic bidirectionality.

After careful analysis of the economic tradeoffs of the various techniques, AT&T decided that a single-fiber system was the best option for the lowest cost system to provide only narrowband services.

The system was required to operate over a range of 3.6 km (kilometers). The outside-plant loss requirement (see Figure 4a) established for the system design was 8.2 dB, which includes some margin for repair splices. This exceeds the point-to-point equivalent requirement of 6.5 dB in Bellcore's TA–NWT–00909.[3] But if the system is deployed as a two-fiber, analog AM (amplitude modulation) video and narrowband system[4] (where video is on the second fiber), then the outside-plant loss is limited by the video transmission parameters and exactly meets the Bellcore requirements. This may seem to be very high loss for a 3.6-km range. However, it is important to understand that distribution plant typically contains many splices because of the high degree of branching and tapering of the fiber network within this portion of the loop.

Optical Device Technology. The most fundamental optical parameter to be dealt with is the choice of wavelength. Three wavelength windows are available: 800 nm (nanometer), 1310 nm, and 1550 nm.

In many respects, the 800-nm window is attractive. The lasers made for compact disk players operate at 800 nm and are available at low cost. These lasers are

packaged and screened for reliable operation in the telecommunications environment and have enough optical power output to overcome the increased fiber loss at these short wavelengths (i.e., 800 nm). The primary difficulty with the use of short-wavelength devices is that there currently are no standards on the use of the short-wavelength window on single-mode fiber, although the Telecommunications Industry Association is developing such a standard. The real issue is that single-mode fiber is no longer single mode below about 900 nm. Without these standards, our customers are unlikely to support the use of the 800-nm window.

We ruled out the 1550-nm window because of the lack of widespread availability of 1550-nm devices, their increased cost (over 1310-nm devices) where available, and technical issues involved with their operation and reliability in high-temperature applications.

Given this, the wavelength choice was 1310 nm. Either surface-emitting LEDs (light-emitting diodes), edge-emitting LEDs, or lasers could be considered as the optical source.[5]

Surface-emitting LEDs would represent the most cost-effective solution, both from a device-cost viewpoint and because of the simplicity of the required drive and control circuitry. However, the coupled output power into single-mode fiber was deemed inadequate. Edge-emitting LEDs offer greater coupled output power than surface-emitting LEDs, but at a cost that approaches lasers. Also, their increased drive-circuit complexity approaches that of a laser driver. For these reasons, the system uses lasers as the optical sources.

The laser used in the system is optimized for this application. Typical telecommunications lasers and their packaging have been optimized for long-haul operation. In such applications, the goals are very high coupled output power and speed. These requirements lead to:

- Expensive, low-capacitance and low-inductance packages
- Thermoelectric coolers
- Stringent requirements on the laser chip itself.

For our application, the laser operates at 1.544 Mb/s and needs only modest output power; therefore, the chip and package requirements were considerably relaxed. Also, in FTTH applications, the cost and power dissipation associated with thermoelectric cooling is undesirable. Therefore, we designed the laser and associated drive circuitry to accommodate an operating temperature range from –40°C to +85°C, without the use of a thermoelectric cooler.

Transmission Architecture. The most direct way to obtain bidirectional transmission on a single fiber is to use the optical equivalent of the hybrid transformer[6] used in a standard telephone set and to transmit in both directions at baseband. The optical equivalent of this transformer is a 2 × 2 optical coupler with one port terminated in the characteristic impedance (i.e., the refractive index) of the fiber. Figure 4a shows this technique.

This technique has the same shortcomings here as it does for a *two-wire*, twisted-pair copper network. That is, it is sensitive to reflections in the network, and the coupler at each end introduces (ideally) 3 dB of loss. The advantages of the technique are that simple electronics are needed for the transmitter and receiver, and the optical assemblies (including the transmitter and receiver) are identical.

We can overcome the reflection sensitivity in several electronic ways. One method is echo cancellation, which is used in the long-haul networks. Another is to separate the two directions of transmission in the time domain via time-compression multiplexing. However, both methods still require splitters (and their inherent loss) and complicate the required electronics.

Obviously, an optical way to reduce (but not necessarily eliminate) reflection impairments is to use wavelength-division multiplexing to separate the two directions of transmission. However, this does not come without certain drawbacks, including extra cost.

Because the single wavelength, baseband transmission architecture was so attractive, we analyzed the effects of optical reflections on system performance. A theoretical analysis[7] showed that, if the signal-to-interference ratio (SIR) was greater than 6.5 dB, then the degradation in receiver sensitivity caused by near-end, reflection-induced crosstalk could be kept below 1 dB. (This was verified by experimental data.)

Next, we generated a model of what could be viewed as the most extreme loop configuration (Figure 4a). The loop length is 6.5 km, which exceeds the maximum specified length by more than 50 percent. There are four standard splices in the outside plant, one drop splice, four repair splices, one cabinet entrance splice, two WDMs (for possible upgrade use), four connectors, and two optical couplers. All contribute reflections. To model the system more accurately, we used the statistical loss and reflection parameters to calculate the system performance. (Since we did this study, the reflection statistics have improved compared those we

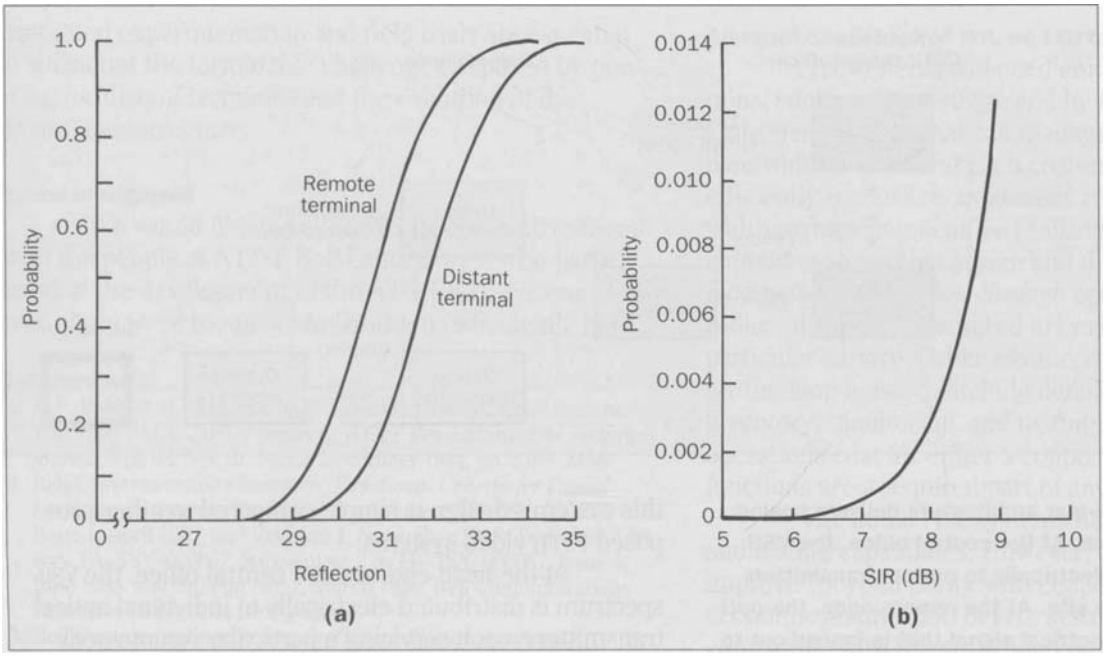

Figure 5. Results of analysis for link model. (a) Total link reflection generated using Monte Carlo methods. Statistical loss and reflection parameters were used to calculate the system's performance. The reflection statistics have since improved. (b) SIR probability of FTTH link for an extreme configuration that is operating at its performance limits.

used.) Figure 5a shows the total return loss statistics we generated using Monte Carlo methods. The data shows the probability of a return loss value of less than 27 dB is less than 0.0001.

We also calculated the signal-to-interference ratio for this link. To stress the system to its limit, we:

- Used end-of-life values for all components.
- Assumed worst-case temperature conditions.
- Added the 3-dB recommended system margin as excess loss to the signal, but not to the reflected interference.

Figure 5b shows the tail of the calculated SIR for this extreme configuration, which is operating at its performance limits. As we can see, the probability that the SIR will be below the 6.5-dB limit is less than 0.0005. In the real world, this implies that the probability that any system will fail because of optical reflections, for all practical purposes, is zero.

Optical Interface Lightguide Unit. Figure 4b is an exploded view of the optical interface unit (OILU), which serves as the interface to the optical medium.[5] The InGaAsP laser and InP-InGaAs backface monitor (which is used to monitor the laser output power) are mounted in an inexpensive, hermetically sealed package. The detector used is a low-capacitance, low dark current, InP-InGaAs PIN photodiode. The splitter is fabricated using fused, tapered-fiber technology. "Fiber pigtails" connect these components and an optical connector.

All the optical and electrical components are mounted on one side of the circuit board. A plastic organizer securely houses the optical components and pigtails to protect them during assembly and handling of the circuit board. Because of the open area in its design, the organizer surrounds electrical components on the circuit board. The result is a rugged final assembly that can be handled the same as any other circuit board.

System Evolution. So far, our description of the FITL system has focused on an implementation for cost-effective delivery of narrowband services. Clearly, the long-term goal of FITL is to support broadband services. But in the short term, legal, regulatory, and business issues inhibit the deployment of these services in the telephone industry.

Today, the only commercially proven broadband service available to residential subscribers is entertainment television. TV signals are delivered to homes in three ways:

- Over-the-air broadcast, at VHF and UHF frequencies.
- Satellite, predominantly at C-band.
- Coaxial cable, at 50 MHz (megahertz) and above. This transport method is referred to as CATV.

Currently, CATV is available to 85 million homes. A large, nationwide, coaxial-cable network links the service providers with the programming providers. In

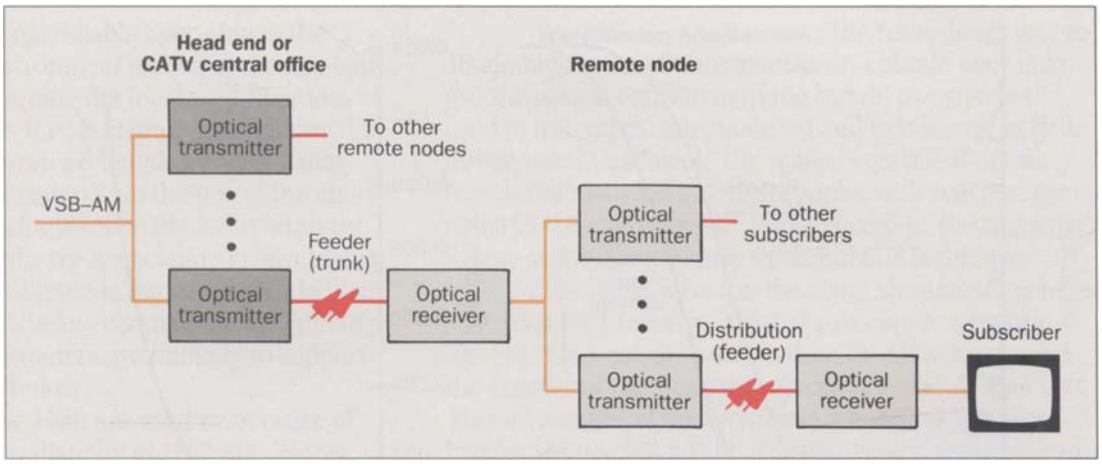

Figure 6. A simple double-star architecture delivers analog VSB-AM video to the home. At the central office, the VSB spectrum is distributed electrically to optical transmitters, one for each remote-node site. At the remote node, the optical signal becomes an electrical signal that is fanned out to optical line cards that reconvert it to the optical domain. From there, the optical video signal is transmitted over a separate fiber in the distribution part of the plant to each distant terminal, which reconverts the signal to the electrical domain and distributes it to subscribers via coaxial-cable drop wiring.

addition, a large base of customer-premises equipment exists that is designed to interface directly with this service. In the United States, over 50 percent of the TV sets and nearly all the video-cassette recorders (VCRs) have inputs that are defined as *cable ready*. That is, they can interface directly with the output from the coaxial cable without any frequency or format translation.

CATV transmission uses a VSB–AM format; that is, vestigial sideband, amplitude-modulated channels are multiplexed together via frequency-division multiplexing (FDM).[4] This is a broadcast form of transmission, where all channels are delivered simultaneously to a subscriber and the TV set or VCR selects the correct channel.

AT&T is using the same philosophy for video as has been described for the narrowband services. Its initial introduction of video transport for the FTTH system will deliver the TV channels via VSB–AM FDM transmission.

Architectural Considerations. Figure 6 shows the distribution of functionality for a VSB–AM video system configured in a star–star architecture. As can be seen, this system's design is simple compared to other proposed FTTH video systems.

At the head end or CATV central office, the VSB spectrum is distributed electrically to individual optical transmitters, each servicing a particular remote-node site. At the remote node, the optical signal is converted back to an electrical signal that is then fanned out (distributed) again to individual optical line cards that reconvert the signal to the optical domain. From there, the optical video signals are transmitted in the distribution part of the plant (perhaps, after being optically split two to four ways based on today's technology limits) to distant terminals. At this point, the signal is reconverted to the electrical domain and distributed to the subscribers via coaxial-cable drop wiring, just as it is today. The system's current design uses a separate fiber in the distribution part of the plant for video transmission.

Summary

FITL is not a revolution, but an important next step in the evolution of the access network that began over a decade ago. Experience with FITL deployment is needed to help guide and drive technology and system features toward practical adaptations.

To date, we have learned that economic parity with copper demands FTTC, with each distant terminal serving 8 to 12 living units. We have also learned that active and passive optical-access architectures are at rough economic parity with each other for delivery of narrowband service. Thus, the choice of architecture will be dictated by other considerations, such as the upgrade to broadband services and local preference. Finally,

continued experimentation and field trials are essential to surmount the formidable challenges imposed by powering for distant terminals and the evolution of the OAM&P infrastructure.

Acknowledgment

We would like to acknowledge the contributions of all the people at AT&T Bell Laboratories who participated in the development of the AT&T FITL system. However, there were too many to list them individually here.

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Appendix A. Effect of FITL on LEC OAM&P

FITL systems will need enhanced OAM&P functions, such as those suggested by Bellcore's TR303.[8] Only FITL systems that can manage the large amount of bandwidth available at each customer's location can efficiently use switch and feeder resources. Such bandwidth management can be realized only by operations support systems that assign and directly administer the loop network. This *flow-through* operation is essential to reduce the activity required of craftspeople to install a particular service. Other advanced operations required for the loop network include detailed alarm reporting, inventory, monitoring, and testing. Because they reduce operations cost for either a copper or FITL network, these functions are a required part of any network upgrade.

The initial FITL systems had simple maintenance and testing capabilities. However, these areas had to improve (beyond parity with copper systems) to aid the economic justification of FITL systems. Testing must be compatible with the embedded base of MLT-LMOS generics and test-center operations and procedures, yet must offer enough reliable information for repair people to be dispatched accurately. (MLT-LMOS is the loop-maintenance operations system for mechanized loop testing. *Generic* refers to a specific version of the software system.) Tests of FITL systems deployed in cluster arrangements must also report the status of the copper drop beyond the distant terminal.

For these new OAM&P functions to be available in a timely way, the LECs and Bellcore need to develop plans to provide the necessary interfaces and new capabilities in the infrastructure for these operations support systems.

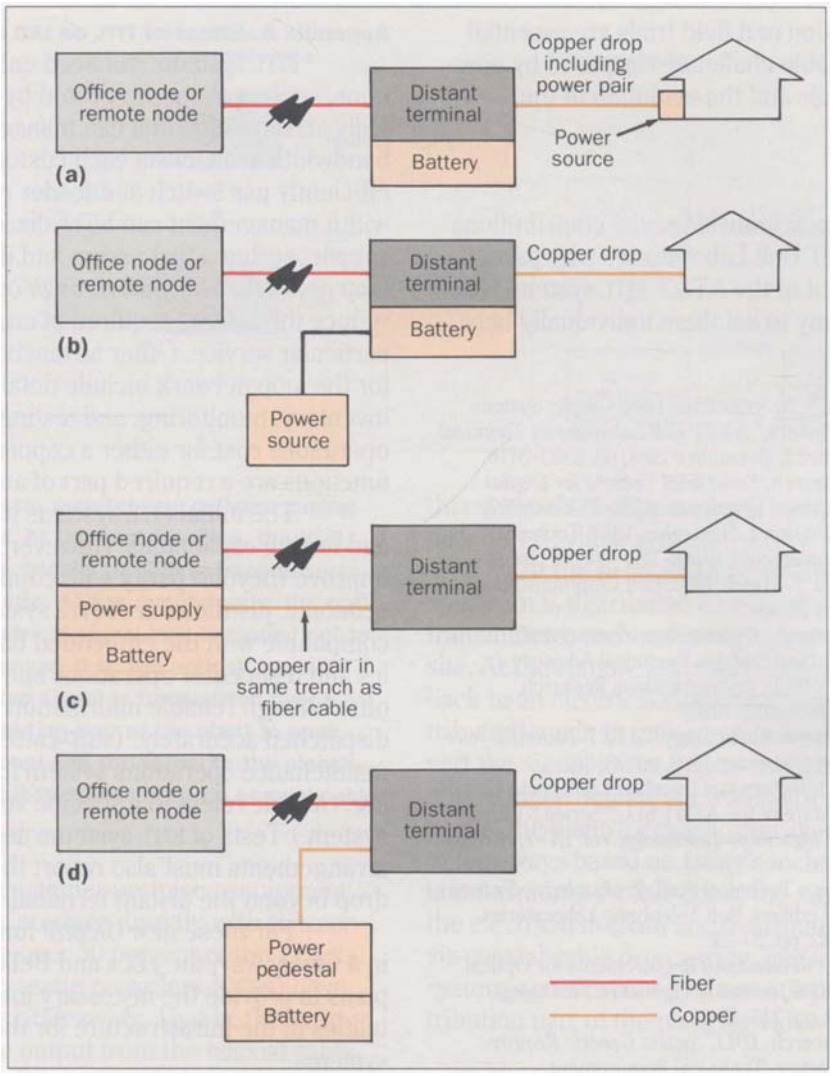

Figure B–1. Powering alternatives for fiber to the curb. For local power from (a) the subscriber or (b) the power utility company, the issues are reserve service time, batteries located in scattered sites, service life of the batteries, and the source of primary power. For network power from (c) the central office or (d) a remote power unit, the issues are the costly copper powering network and savings in long-term maintenance.

Appendix B. Distant Terminal Powering

The change to a cluster configuration affects distant-terminal powering. Usually, a distant terminal located on the side of a house was powered locally. Such an arrangement was easy to provide in new constructions, but required costly electrical work at each living unit in rehabilitation areas. When the distant terminal is moved to the curb, local powering becomes more difficult to obtain, yet network powering becomes feasible (from a shared central source, such as the remote terminal). Powering arrangements certainly affect the cost of the FITL system. Therefore, a detailed analysis of both local powering (Figures B–1a and B–1b) and network powering (Figures B–1c and B–1d) is required.

Clearly, regulatory agencies, electrical codes, and local practices, together with the average and peak power demands of the distant terminal, impose limitations that rapidly constrain the application of these distant-terminal powering alternatives. What determines the amount of power a distant terminal requires is the design of the optical and electrical interface and the station equipment—such as telephones, answering machines, and connected telemetry systems—that are embedded in the existing network. One may entertain the notion of new telephones designed specifically for FITL applications. However, one cannot ignore the reality of several hundreds of millions of telephones that were built to work with the existing network, and regulators

who are concerned about technical decisions and how they affect what consumers pay for service.

In the United States, Bellcore's TR57[2] is a dominant, current standard that affects electronics in the local loop. This standard has been interpreted to determine:

- How many telephones a fiber distant terminal must serve
- What the loop current must be
- How many ringers may be on a single line
- How many lines from a given distant terminal may be ringing simultaneously.

A conservative reading of TR57 results in a demand for high power levels.

In addition, TR57 was originally written for traditional loops that had a maximum length of 12,000 feet and it did not address short loops adequately. Because FITL systems always feed short loops, the opportunity exists to optimize transmission parameters for this case and thereby reduce power requirements.

Most cost studies of powering alternatives for FITL systems under existing constraints show a clear first-cost advantage for local powering. However, this configuration raises several concerns about the performance, reserve time, life expectancy, monitoring, and replacement of the multitude of local batteries spread throughout the outside plant. Network powering does address these issues, but it requires a copper path to each distant terminal.

New battery technology, sophisticated monitoring systems, reduced-power operation, and new standards will contribute finally to a power solution. In the meantime, vendors must provide both alternatives to enable LECs to select the solution that best meets local requirements.

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Peter P. Bohn *is a supervisor in the Loop Systems Planning Department with AT&T Bell Laboratories in Whippany, New Jersey. He is responsible for system engineering on fiber-in-the-loop systems. Mr. Bohn joined the company in 1972 with a B.S.E.E. from the University of Bridgeport (Connecticut), and both an M.S.E.E. and a Ph.D. in electrical engineering from Stevens Institute of Technology (Hoboken, New Jersey).*

Michael J. Kania *is a product manager in the Fiber to the Home Department with AT&T Network Systems in Whippany, New Jersey. He is responsible for product planning and business management of AT&T's line of fiber-to-the-home products. Mr. Kania joined the company in 1968. He has a B.S.E.E. from City College of New York (New York City) and an M.S. in engineering management from New Jersey Institute of Technology (Newark).*

Joseph M. Nemchik *is a supervisor in the Loop Fiber Systems Development Department with AT&T Bell Laboratories in Whippany, New Jersey. He supervises the development for fiber-in-the-loop products. Mr. Nemchik joined the company in 1970. He has a B.S.E.E., an M.S.E.E., and a Ph.D. in electrical engineering, all from Carnegie-Mellon University (Pittsburgh, Pennsylvania).*

Robert C. Purkey *is a supervisor in the Digital Loop Carrier Systems Department with AT&T Bell Laboratories in Whippany, New Jersey. He is responsible for systems engineering of the SLC–2000 carrier system. Mr. Purkey joined the company in 1968. He has a B.S. in aerospace engineering from the University of Cincinnati (Ohio), an M.S. in aerospace engineering from the University of Michigan (Ann Arbor), and an M.S. in operations research from George Washington University (Washington, D.C.).*