TERRESTRIAL LIGHTWAVE SYSTEMS

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Lightwave is one of the three foundation technologies of AT&T's vision of universal information services. The growth in the telecommunications use of glass fibers could not be predicted just six years ago when AT&T deployed the FT3 system, its first lightwave transmission product. Today, fiber carries digitally encoded voice, data, and video services in the terrestrial loop and trunk, as well as undersea applications. This paper focuses on terrestrial applications of lightwave systems for metropolitan and long-haul trunking. After a brief review of the progress in the last six years, we will examine the forces that drive the need for lightwave systems today and the systems we offer to meet it. We will then try to predict the future of terrestrial lightwave systems in the second half of the 1980s—the Lightwave Decade.

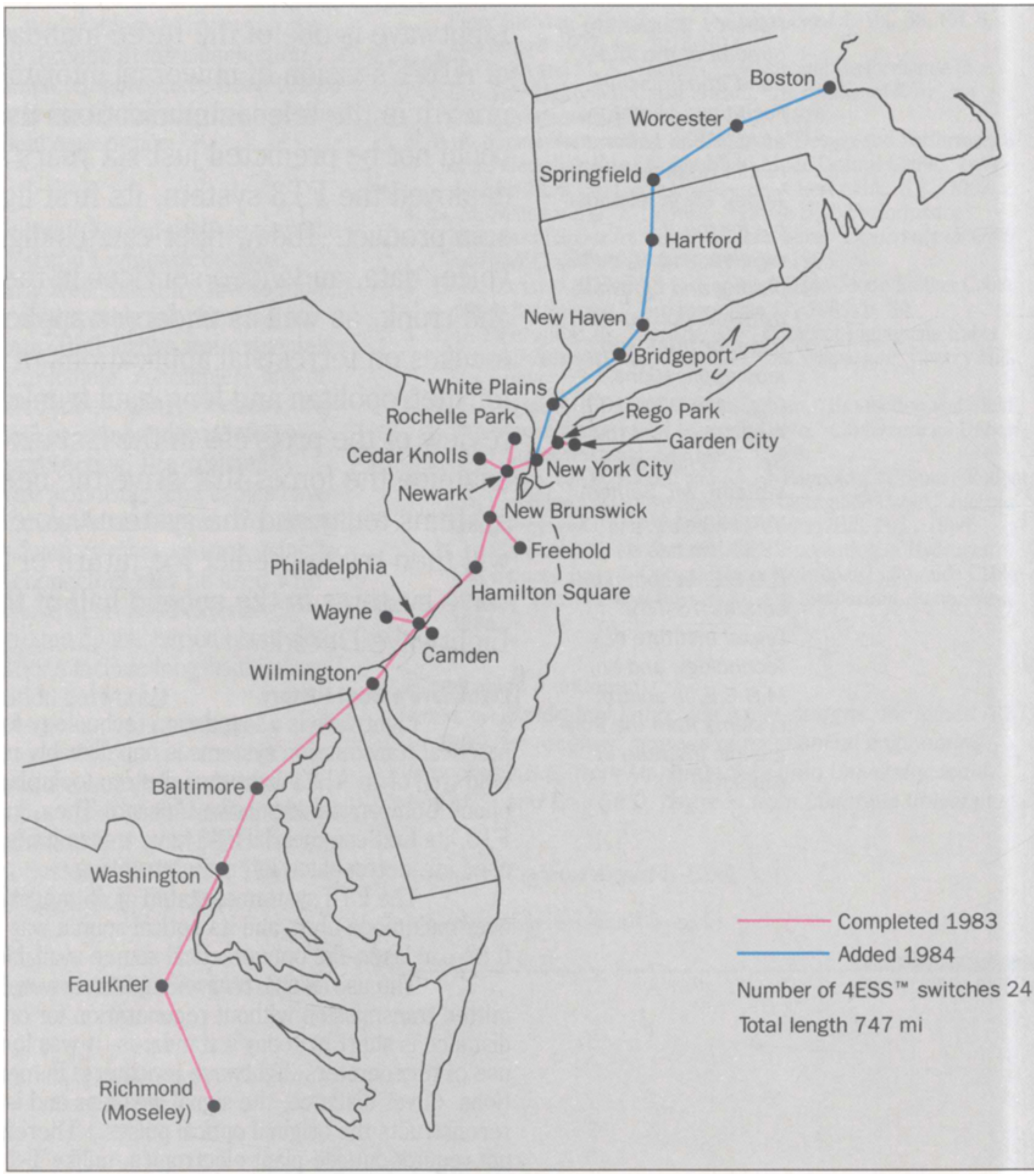
Lightwave's Brief History

Lightwave is a foundation technology for AT&T, yet its use in practical transmission systems is unbelievably recent. In 1977, the first field trial of an AT&T lightwave system took place in Illinois Bell Telephone Company in downtown Chicago. Then, in 1980, AT&T introduced FT3, its first commercial lightwave transmission system. It was first used for metropolitan interoffice trunking.

The FT3 system operated at 45 megabits per second (Mb/s) over multimode fiber, and its optical source was a short wavelength 0.82-μm laser, the only practical source available at the time.

The use of short wavelength lasers on multimode fibers permitted transmission without regeneration for only 7 km. Although this distance is short by today's standards, it was long enough to avoid the use of regenerators (lightwave repeaters) in many interoffice applications. (Over distance, the signal weakens and is distorted; a *regenerator* reconstructs the original optical pulses.) Therefore, the FT3 system did not require outside-plant electronics, unlike T-1 and the other digital

Figure 1. AT&T's fiber optic network for the Northeast Corridor. The section between New York and Washington, D.C., went into service February 1983. The New York to Boston section was added in 1984.



carrier systems at that time.

This absence of outside-plant electronics was especially attractive in two early lightwave applications. One system crossed above San Francisco Bay on the Golden Gate Bridge and the other below the Bay in the tunnel for the BART (Bay Area Rapid Transit) Line.

Another important advantage over T-carrier was lightwave's efficient use of precious duct space in metropolitan areas. A single fiber operating at 45 Mb/s replaced 28 copper pairs that operate at the T-1 rate of 1.5 Mb/s.

Synergy with Digital Switches. The first major long-haul application of lightwave was in early 1983 by AT&T Long Lines along the New York to Washington, D.C. section of the *Northeast Corridor* between Boston and Washington (Figure 1). The New York to Boston section was completed in 1984.

In its application to the Federal Communications Commission for approval of the route's construction, AT&T pointed out that constructing a lightwave system was about 20 percent less expensive than the alternative of increasing the capacity of existing analog facilities. The savings occurred because digital-to-analog conversions were not needed to interconnect 23 4ESS™ switches along this route.

The use of a high-capacity, digital lightwave transmission system to provide trunk connections between the digital switches was an early example of the powerful economic synergy between digital switching and digital transmission.

The Northeast Corridor was the first application of the FT3C system—a member of the FT3 family—that operated at 90 Mb/s, which at the time still used 0.82-μm laser sources on multimode fiber.

But in 1983, two important technology changes occurred. First, longer wavelength 1.3-μm laser sources were introduced. Lower fiber loss at the longer wavelength permitted us to increase the repeater spacing from 7 km to 25 km.

The second important transition was the change from multimode to single-mode fiber, and its importance is related to two penalties in optical transmission: chromatic dispersion and modal dispersion.

Chromatic dispersion is caused by differential delay in a glass fiber as a function of the wavelengths that are present in a pulse of light.[1] The lasers used in lightwave systems to date are not pure, single-wavelength sources; their spectra consists of several distinct wavelengths. In conventional single-mode fibers, chromatic dispersion is lowest near 1.3 μm, so this effect is minimized with today's impure 1.3-μm laser sources.

The second effect is modal dispersion. In multimode fiber, which has a large core diameter, a pulse of light is permitted to propagate (travel) along different paths that have different lengths. Thus, it arrives at the optical detector at different times and is broadened, or smeared; this is called *modal dispersion.* As the bit rate increases, there is increased overlap and, therefore, interference between adjacent pulses and the modal dispersion penalty increases. Thus, we eventually reach a practical bit rate limit.

The most important advantage of single-mode over multimode fiber is that it avoids this modal dispersion because light can propagate only along a single path in its small diameter core. Consequently, single-mode fiber does not have a practical bit rate limit with laser sources that operate at the dispersion minimum. What limits the bit rate on the fiber is the speed of the lightwave system's electronics and optical components that drive it.

System Upgrade. Part of AT&T's original plan for the Northeast Corridor was an upgrade to 270 Mb/s per fiber using a technique called wavelength-division multiplexing (WDM)—the simultaneous transmission of multiple wavelengths (colors) of light down the same fiber. WDM permits one fiber to transport the signal from more than one lightwave system. Thus, when the highest bit rate available at the time is not enough to meet service demand, we can get more capacity on that fiber with WDM (Panel 1).

Originally, we planned to use three-wavelength WDM to overbuild the original 90-Mb/s signal that oper-

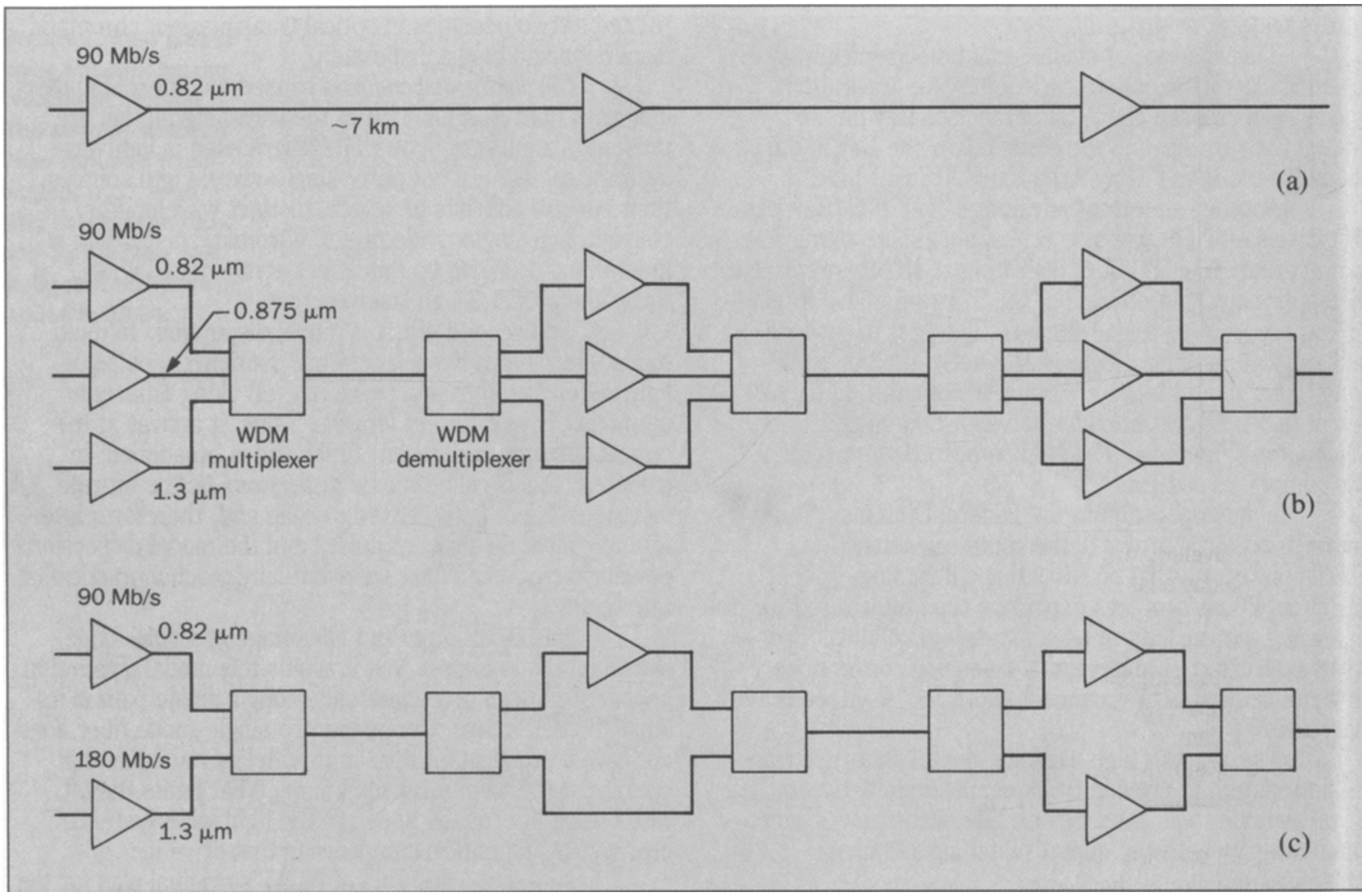
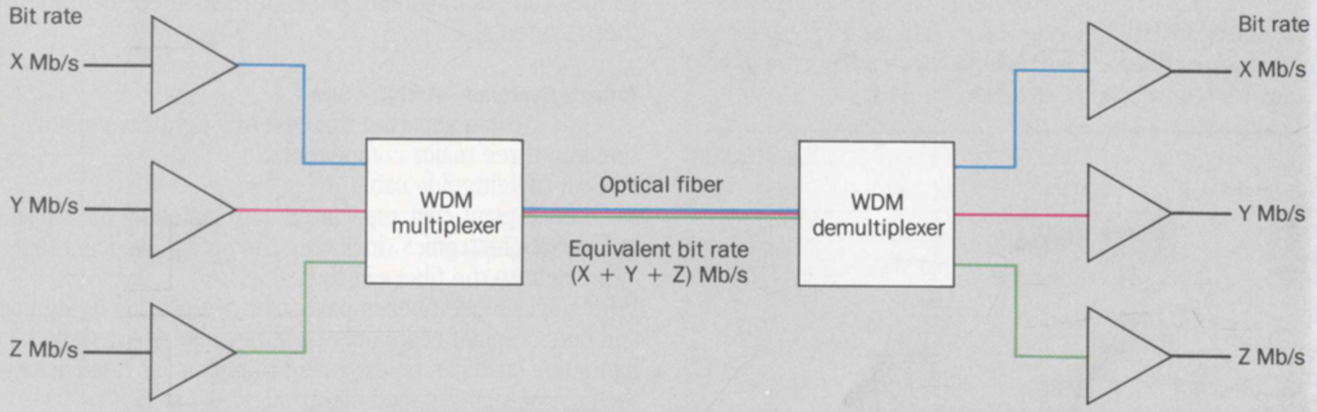


Figure 2. Wavelength-division multiplexing (WDM) upgrade for the Northeast Corridor: (a) Initial installation, 90-Mb/s capacity. (b) Original upgrade plan, 270-Mb/s capacity, four regenerators added for two sections. (c) Final installation, 270-Mb/s capacity, one regenerator added for two sections.

ated at 0.82-μm with two more 90-Mb/s bit streams at different wavelengths, 0.875-μm and 1.3-μm. (An *overbuild* is an incremental installation on an existing facility to increase its capacity, usually done in a way that minimizes the impact on the existing services.)

Through technology advances, we achieved that capacity in 1984 with the addition of a single FTX-180 overbuild on the route that operated at 180 Mb/s with a 1.3-μm laser source. The lower fiber loss at 1.3-μm permitted us to skip regenerators at every other repeater site. Overall, only one-fourth of the additional regenerators in the original plan were required for this WDM upgrade (Figure 2).

A Growing Network. In 1985, the first FT Series G



Panel 1: Wavelength-Division Multiplexing

Today's lasers, while not perfectly monochromatic, have a narrow-band optical spectrum. Lasers are available with spectra centered at different wavelengths (colors). Optical filters are available for mixing, or multiplexing, these sources into a single *multicolor* optical signal that can be transmitted along an optical fiber. At the far end, similar optical filters permit separating, or demultiplexing, these colors so that each receiver *sees* only the single color of light launched from its mate transmitter at the far end. This technique, called wavelength division multiplexing, permits multiple signals at a given rate to be transported on the same glass fiber, thereby reducing the fiber count required to carry a given amount of traffic.

system, which operates at 417 Mb/s, was shipped to an AT&T location along a lightguide route between Philadelphia and Chicago. It was the first stage in AT&T's deployment of FT Series G in a nationwide, integrated digital network to be in place by the late 1980s.

This year, extensive deployment is continuing in AT&T, as well as in several Bell Operating Companies and LIGHTNET, a carrier's carrier that leases fiber capacity to other companies. In 1987, AT&T's Philadelphia-Chicago route and other routes will be upgraded to operation at 1668 Mb/s. At this bit rate, we can transmit the entire contents of the *Encyclopaedia Britannica* in less than two seconds (Panel 2).

Lightwave's Capability

As the bit rate of these systems has increased, so has the repeater spacing, which is up to 46 km of lightguide cable for FT Series G.

The product of bit rate and repeater spacing is an interesting measure of lightwave technology's capability. Figure 3 shows the history of this parameter for the systems just discussed. Roughly every three years, there has been tenfold improvement in this parameter and a corresponding decrease over time in the cost per bit-kilometer. How have these improvements changed the economics of lightwave deployment since it was first introduced?

In early metropolitan applications, we usually

Panel 2: Voice Circuit Equivalents

AT&T's lightwave systems have provided ever-increasing capacity to carry voice, data, and video circuits on glass fibers. This table illustrates the growth in circuit-carrying capacity of these systems.

System	Year introduced	Bit rate	Voice-circuit capacity
FT3	1980	45 Mb/s	672
FT3C	1983	90 Mb/s	1344
FTX-180	1984	180 Mb/s	2688
FT3C + FTX180 WDM capability	1984	270 Mb/s (equiv.)	4032
FT Series G 417	1985	417 Mb/s	6048
FT Series G 417 WDM capability	1986	834 Mb/s (equiv.)	12096
FT Series G 1.7	1987	1668 Mb/s	24192

could not justify lightwave over T-carrier alternatives based on first-cost savings. But other factors—fewer repeaters in the outside plant, savings in duct space, and lower maintenance cost—justified these installations. In long-haul applications, lightwave's synergy with digital toll switching produced an immediate first-cost savings over alternative facilities (radio, coaxial carrier, satellite).

Today, the rapid improvement in cost and performance of lightwave systems has made lightwave the technology of choice in most interoffice trunking applications, both metropolitan and long-haul. This *digitization* of these facilities, as well as lightwave's penetration into the loop plant that provides access to these networks[2] has spurred the growth of important new digital services: for example, AT&T's Accunet® 1.5 and T45 services (1.5- and 45-Mb/s service, respectively, to the customer).

The same rapid improvements can be viewed another way: A system will be out of date by an order of magnitude in performance only a few years after it is first deployed. Therefore, customers demand that we design lightwave systems that can be upgraded to higher line rates so they can get maximum reuse of their investment in these systems.

Today's Systems—Architecture

We can separate the cost of a lightwave installation into three major components:

- Cost of lightguide cable
- Outside-plant cost associated with installing the cable
- Cost of electronics (including the optical devices) that connect to the fibers in the cable.

With single-mode fiber in particular, we pay the lightguide and outside-plant costs only once because the installed lightguide base can be upgraded to higher bit rates at only the cost of higher speed electronics.

The electronics have four main components (Figure 4). Three perform the transmission function:

- The *terminal multiplex* equipment converts the incoming digital signals from the office to the bit rate on the line (the line rate).
- The *terminal regenerators* do conversions between the electrical line rate and the pulses of light on the fiber.
- When required, the *line regenerators* reconstruct the original optical pulses to increase the allowable distance between the terminals.

The fourth component consists of an overlaid *maintenance subsystem* that does several important tasks:

- Monitors the error rate performance of the system.
- Automatically switches transmission to a protection line when a service line has an unacceptable error rate or is interrupted.
- Alerts remote maintenance personnel when problems occur in the system and directs the maintenance activity to the source of those problems for replacement and repair. This involves diagnosing terminal failures and locating faults to find regenerator failures along the line.

The regenerator design is tightly coupled to the line rate of the system. Therefore, when the system is upgraded to a higher line rate, the regenerators must be replaced. But the upgraded system can reuse the terminal

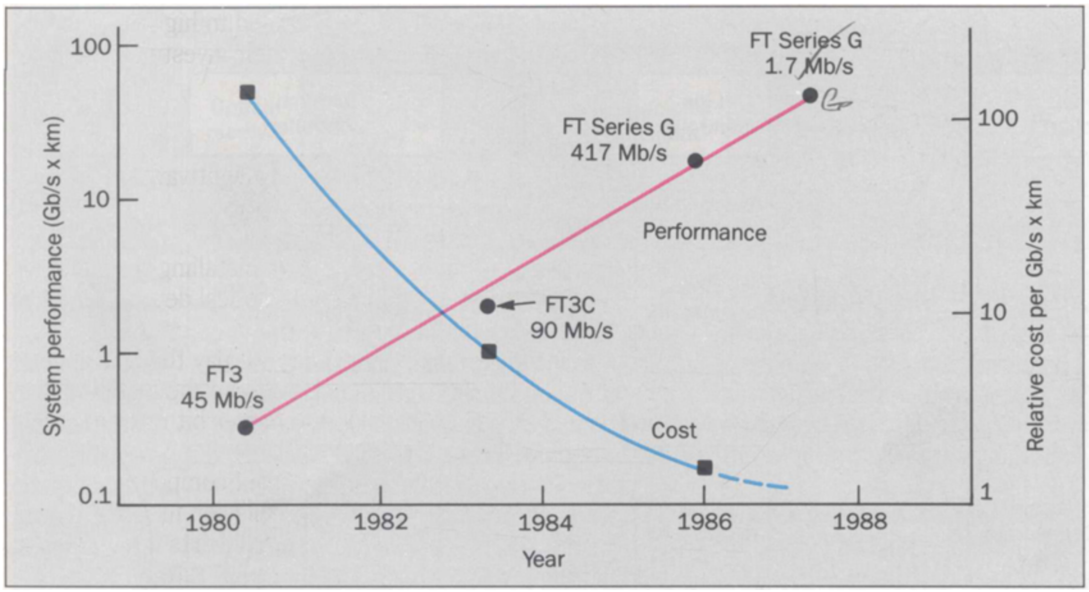


Figure 3. Performance and cost of AT&T lightwave systems.

multiplex equipment and maintenance subsystem, which meets the customers' demand for flexibility.

Another important attribute of system design is modularity. This means the system can be installed to meet the initial service need and incrementally expanded as the need for service grows.

For example, FT Series G is both modular and upgradable. After the initial installation, it can be upgraded to provide economical expansion to meet new service needs (Appendix A). Capacity at the terminals can be added one DS3 signal (44.736 Mb/s) or one line (nine DS3 signals at 417 Mb/s) at a time without large amounts of additional common equipment, so both start-up and incremental costs stay as low as possible.

Flexible Components. The heart of the terminal is an 8-inch by 10-inch synchronizer/desynchronizer (SYNDES) card for each DS3 signal.

The card embeds the DS3 44.736-Mb/s signal into a 46.32-Mb/s internal signal that is synchronous with the terminal electronics. The higher internal-system rate accommodates variations in the clock frequency of the incoming DS3 signals, which are asynchronous in today's digital networks. In addition, the card monitors the integrity of the incoming DS3 signal and the system error performance.

These functions are provided by two VLSI (very-large-scale-integration) devices that are built with high-speed, 1.0-μm NMOS (n-type, metal oxide semiconductor) technology.

In addition, circuits on these VLSI devices provide data links that convey maintenance information both between the terinals at each end and from the regenerators on the line. Controllers in the terminal monitor these data links and report the system's status via alarm indications and a local display to on-site craftspeople and a remote surveillance system for centralized maintenance and control operations.

Because the 46.32-Mb/s internal signals are synchronous, they can be simply *interleaved* to form the bit stream at the line rate. At 417 Mb/s, nine of these signals

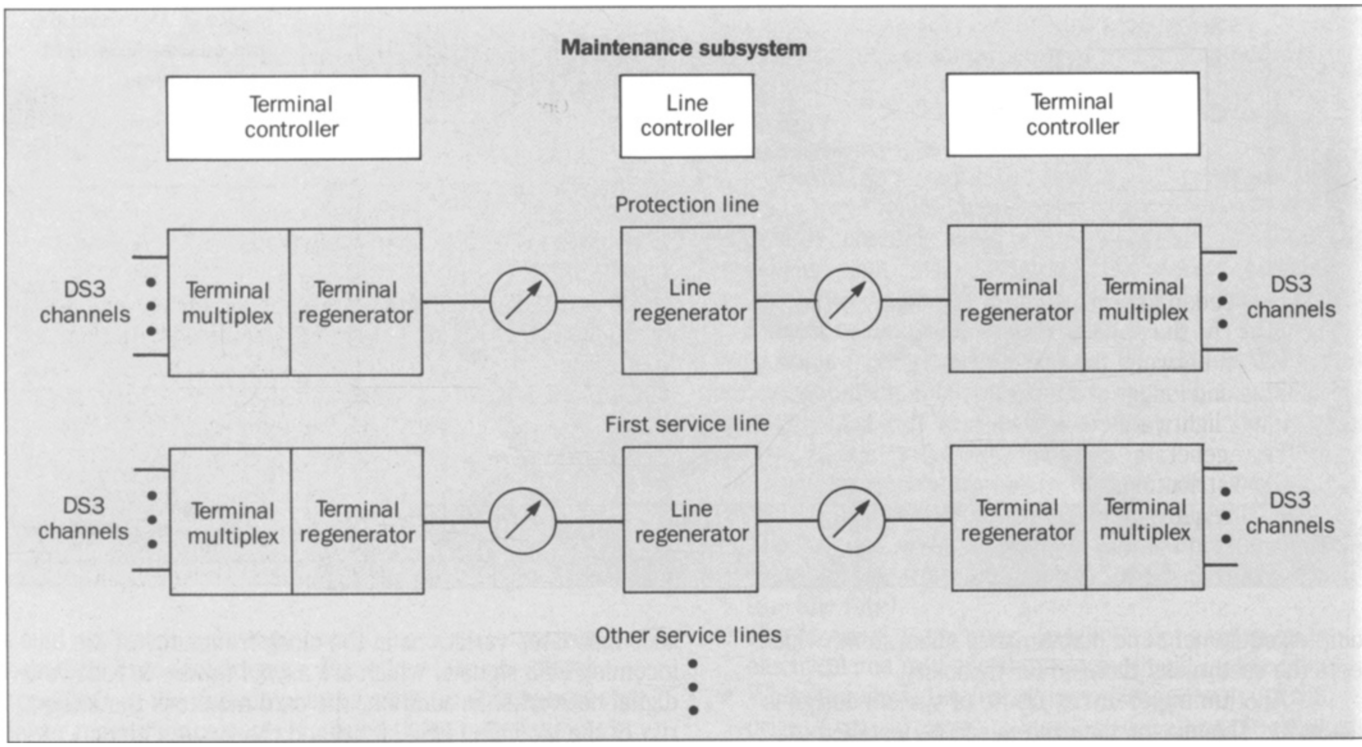


Figure 4. Typical lightwave system. The maintenance subsystem overlays the entire system.

are interleaved in two steps: first to 139 Mb/s and then to 417 Mb/s. At 1.7 gigabits per second (Gb/s), twelve of the 139-Mb/s signals are interleaved to form the 1.7-Gb/s bit stream.

High-speed, submicron NMOS, multiplex and demultiplex devices do the multiplexing from 139 Mb/s to 1.7 Gb/s. They represent the latest in high-speed MOS technology and were developed at AT&T Bell Laboratories in Murray Hill.

As Appendix A shows, the bulk of the system's terminal multiplex and maintenance components can be reused when the system is upgraded from 417 Mb/s to 1.7 Gb/s. By protecting the customer's investment in this equipment, we meet the upgradability objective that was described previously.

Today's Systems—Technology

The technology and engineering issues in the design of regenerators are as exciting as those in the terminal design.

For example, hero experiments can allow repeaterless transmission over hundreds of kilometers. However, some considerations limit the practical regenerator spacing to much less than that, including:

- Statistical distribution of fiber and splice losses
- Parameters of lasers, receivers, and other components

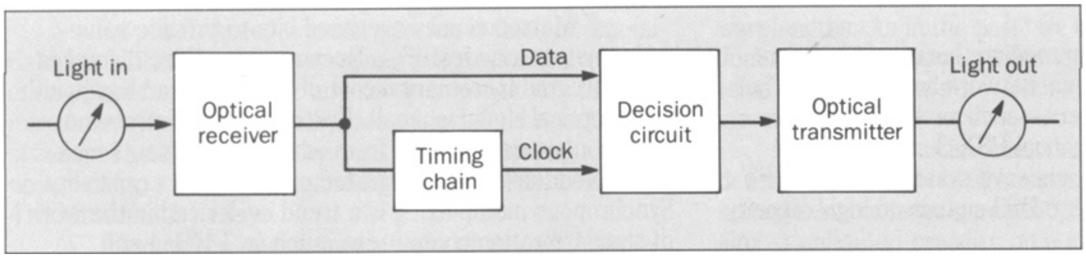


Figure 5. A typical FT Series G lightwave regenerator.

- Margins needed for aging and other effects.

Clearly, the setting of system objectives is an economic tradeoff between the truncation of component distributions and longer span lengths. One engineering judgment in a lightwave system's design is to balance the cost of the regenerator by accepting a larger fraction of the component distribution. But the hard reality is: Shorter span lengths require more regenerators (and may have a negative effect in the marketplace).

Figure 5 shows a block diagram of a typical lightwave regenerator. (The transmitter and receiver contain a laser and photodetector, respectively, that are discussed elsewhere in this issue.[3])

The timing chain in Figure 5 extracts the clock signal from the incoming bit stream so that the bit stream can be retimed. Its key component is a surface acoustic wave (SAW) filter that provides a high-Q resonant circuit at the line frequency. AT&T's current lightwave products use this technique for timing extraction.

Another major element in the regenerator is the decision circuit that determines the value (0 or 1) of the bit stream at each bit interval. In the FT Series G, 417 Mb/s regenerator, this is a silicon integrated circuit. For the 1.7 Gb/s regenerator, the decision circuit is a gallium arsenide (GaAs) integrated circuit that was developed at AT&T Bell Laboratories in Murray Hill, New Jersey, and Reading, Pennsylvania.

The FT Series G regenerator contains an important part of the maintenance system. An on-board, microcomputer-based, *in-service regenerator monitor* measures the regenerator's important parameters to determine its health. It telemeters these measurements over an embedded data link to the terminal where they are compared to previous readings. Minor changes in these parameters are early warning signals of potential problems, and alert the centralized maintenance staff before the customers' service degrades.

Today's Systems—Performance

The lightguide transmission medium is generally insensitive to atmospheric effects and electromagnetic interference. Thus, it provides excellent performance, especially for demanding long-haul applications.

In these applications, the objective is to have a bit error rate (BER) that is better than 10^{-8} for each DS3 channel over a 4000-mile circuit. For shorter distances, the BER requirement is prorated accordingly.

Recently, we measured the bit error rate of a DS3 channel on FT Series G cable for a section of the Philadelphia to Chicago route. A BER of 10^{-8} would translate to 900 errors per day on the section measured. But during a 28-day segment of the test, no errors were measured—a testimony to the quality of the system's design and manufacture.

Put briefly, today's lightwave systems offer high-quality digital connectivity at low cost per circuit. As a result of these attributes, these systems have an enormous penetration in metropolitan and long-haul trunking, as well as loop applications.

We have every indication that the future of these systems will see a continuation of the progress made to date. What will the next five years bring?

Trends in Lightwave Systems

One trend on the immediate horizon is a departure from today's conventional network architecture. That architecture uses multiplexers—such as AT&T's DDM-1000—from DS1 to DS3; manual DSX-3 cross-connect frames; and point-to-point lightwave systems, such as FT Series G, that transport these DS3 signals on high-capacity links.

Metropolitan applications are characterized by densely interconnected trunk networks. In the past, these trunks were implemented on numerous point-to-point T-carrier facilities. Because each facility could carry only a few trunks, the facility network's topology was virtually identical to the trunk network it provided and resembled a mesh-like structure.

When the telephone companies deployed high cross-section lightwave systems in these networks, the facility topology changed. To use these high-capacity links efficiently, traffic was collected into offices that serve as intermediate nodes (the transmission equivalent of a tandem office), with high-capacity lightwave links between these nodes.

This structure is ideal for long-haul applications, where the trunk topology matches this form. But for a highly-meshed metropolitan network, a facility that consists of nodes and links can result in facility arrangements that are less efficient than in the more closely-matched, long-haul applications. While this arrangement is superior to (and cheaper than) T-carrier or other older technologies, it has an element of *square pegs in round holes* that begs for a better fit between the facility and trunk topologies.

To meet this need, AT&T developed a new lightwave transmission system called Metrobus.[4] Its principal advantage is the ability to add and drop small cross sections of traffic, typically at the DS1 level, at many offices. (This is analogous to a *bus* with passengers coming and going at will along the route.) It does this with a novel multiplexing scheme, not the conventional DS1 to DS3 to line rate scheme of today's systems.

Metrobus uses overhead bits to provide value-added networking features. Because interoffice distances are short, the incremental cost of this overhead bandwidth in the optical signal is small. Furthermore, Metrobus uses synchronous multiplexing from which we derive its inexpensive add/drop and integrated cross-connect capability. Synchronous multiplexing is a trend evidenced in the work of standardization committees, such as T1X1.4 and CCITT (International Telephone and Telegraph Consultative Committee).

This arrangement provides a *virtual facility* within Metrobus that matches the mesh-like trunk topology found in metropolitan networks. Metrobus groups the signals that travel in the same direction. Along the way, it may add or drop signals at multiplexers or transfer signals to another path, each time reforming the group.

Flexible control built into Metrobus permits easy administration of new circuits between offices. The close fit between Metrobus's virtual facility and trunking demands and the flexibility that built-in control provides offer a distinct advantage over the manually-administered networks that use today's node and link topology.

In the long-haul arena, the node and link architecture is well matched to the trunking needs, and the principal demand is for higher speed links. The demand for ever-greater line rates reflects the growth of voice-circuit trunking capacity in these networks and explosive demand for digital circuits.

While 1.7 Gb/s (36 DS3s per fiber) seems incredible compared to the 45 Mb/s (one DS3 per fiber) systems of just five years ago, long-haul customers of lightwave systems, including AT&T's, are demanding even higher bit rates in the next few years. The availability of these higher bit rates means substantial savings because fewer fibers, regenerators, and other associated electronics need be deployed to meet these service demands.

We can assume that lasers and detectors can be designed for multi-gigabit performance with little penalty. Of course, there is a fundamental sensitivity loss of 3 dB each time the bit rate is doubled.

In practice, regenerator spacing is fixed during initial installation. Thus, any system's design must have enough laser output power and receiver sensitivity to permit conversion to a higher bit rate with the old regenerator spacing. The FT Series G system, for example, is designed for a maximum span length of 29 miles, both at 417 Mb/s and 1.7 Gb/s.

Beyond the question of laser sources and detectors, the speed of a system's electronics must keep pace with the increase in bit rate. In today's system designs to 1.7 Gb/s, we use both silicon and gallium arsenide (GaAs) discrete and integrated devices for these functions. Only time will tell if the incredible speed advances in silicon technology can keep up with the maturing GaAs technology. (GaAs is intrinsically faster because of its mobility advantage over silicon.)

There is every evidence that the trend in system bit rate will continue beyond 1.7 Gb/s—we don't know how far or how soon. At the same time, there is parallel pressure in the market to increase the repeater spacing of these high bit rate systems, because regenerator costs tend to increase with increased bit rate.

Lasers with higher output powers, as well as advances in receivers with more sensitive avalanche detectors, will continue to increase regenerator spacings.

We also have an opportunity for lower fiber loss using sources with a 1.55-μm wavelength. For example, we can use conventional multifrequency laser sources with fiber whose chromatic dispersion minimum has been shifted to 1.55 μm (dispersion-shifted fiber). But for 1.55 μm on today's fibers with the dispersion minimum at 1.3 μm, we require single-frequency sources because the fiber's chromatic dispersion penalty at 1.55 μm is unacceptably high for operation with multifrequency sources.

The large embedded base of today's fiber creates a market that is driving the development of these single-frequency laser sources.[2,3]

Besides the possibility of increasing regenerator spacing, sources at 1.55 μm make it possible to use wavelength-division multiplexing at the 1.3- and 1.55-μm wavelengths. As in the past, we can use this capability to double the fiber capacity of today's 400- to 500-Mb/s systems and tomorrow's 1.7-Gb/s systems until higher rates are available.

Farther out in time, the application of coherent detection techniques, which permit wavelength-division multiplexing of large numbers of sources, promises an almost unlimited capacity on a single fiber and the possibility of increased regenerator spacing. The integration of the optical transmission function into digital switches and eventual elimination of the electrical-to-optical conversion through optical switching hold the promise of enormously reduced cost and new service opportunities in the future.

Conclusion

The history of lightwave to the present has been a tale of one superlative after another—in the rapid rate of deployment, dramatic system cost reductions, and continual increases in optical line rates. The future of these systems will continue these trends and add the dimension of radical changes in network architectures.

Acknowledgments

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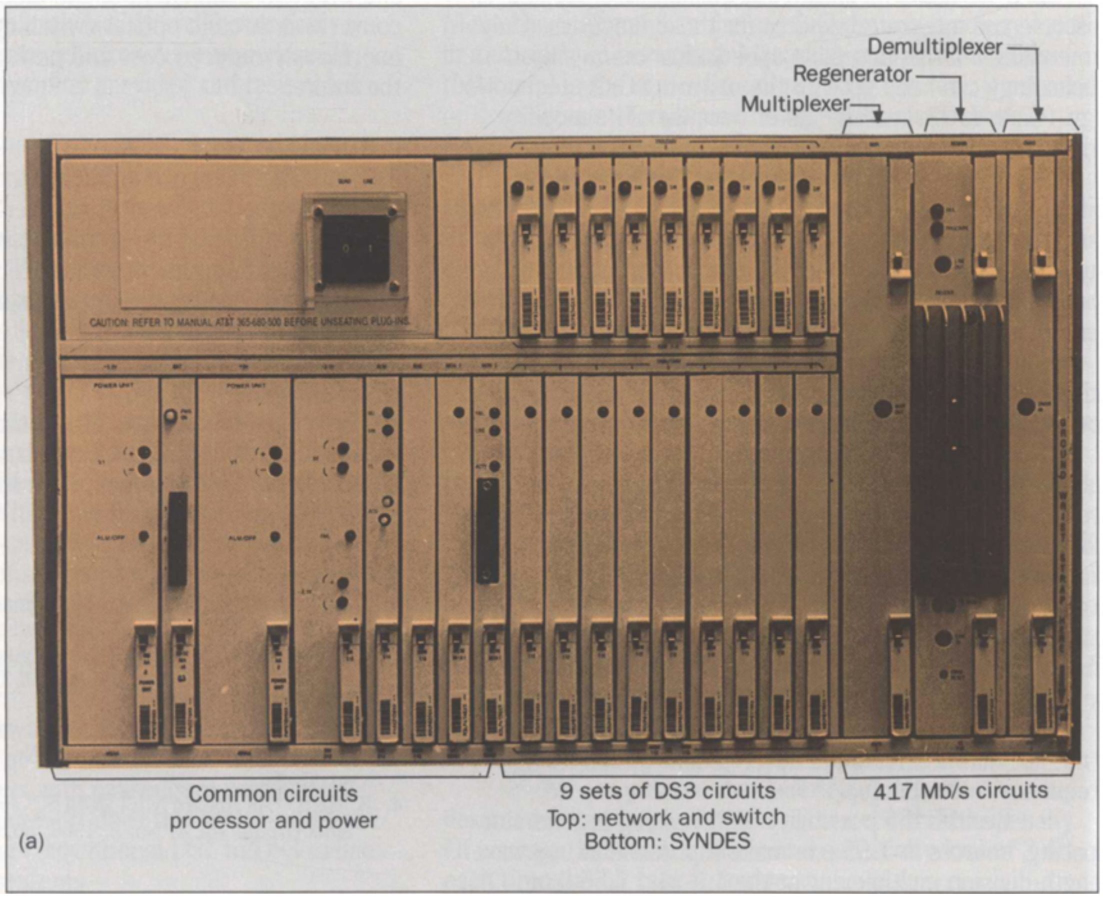
Appendix A. System Modularity and Upgrading

The FT Series G system is both modular and upgradable as the photographs show.

a. The transmitting muldem assembly (TMA) multiplexes nine DS3 (44.736 Mb/s) signals up to a line rate of 417 Mb/s. Then, the 417 Mb/s line signal is transmitted optically—by turning a laser on and off—to a receiving TMA. In the receiving TMA, a photodetector converts the optical line signal to an electrical signal, which is demultiplexed to recover the original nine DS3 signals. Network and switch and synchronizer/desynchronizer (SYNDES) circuits are installed for only as many DS3 channels as the traffic media requires. Because each DS3 channel has an equivalent capacity of 672 individual telephone (voice frequency) channels, a fully equipped TMA can transmit 6048 telephone channels simultaneously.

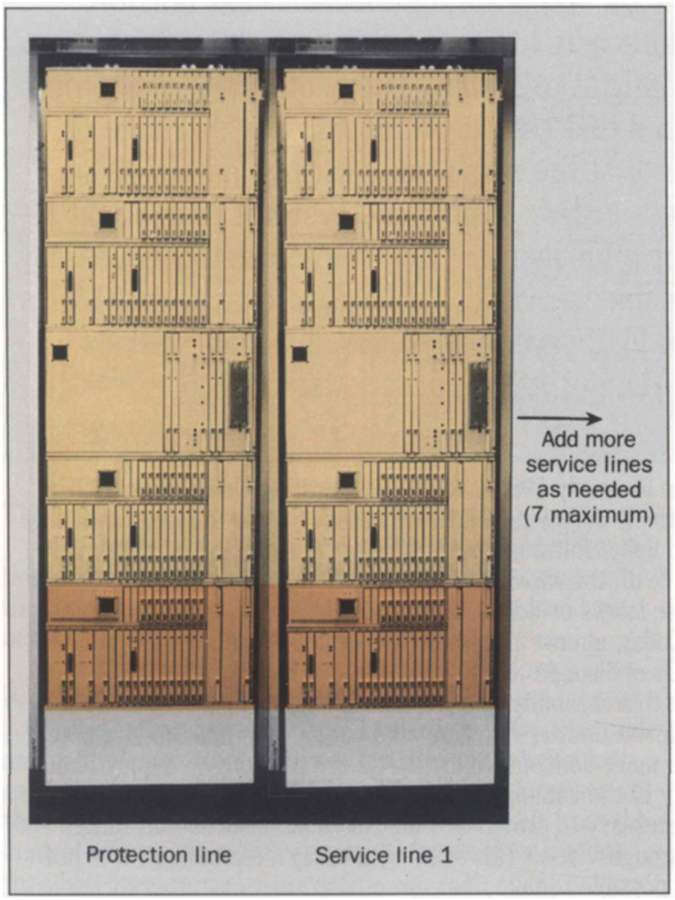
b. TMAs can be arranged in protection switching groups that range in size from 1 × 1 (one protection line for

(a) Transmitting mulden assembly (TMA).



each service line) up to 1 × 7. The system can start with a 1 × 1 configuration, which provides up to 6048 protected telephone channels. By adding more service lines, we can expand the system easily to a 1 × 7 configuration with a maximum capacity of 42,336 protected telephone channels. Line repeaters are required between the TMAs when the distance between offices is too great.

(b) Initial configuration (dark shading) at 417 Mb/s is upgraded to 1.7 Gb/s by adding TMAs (light shading).



c. To put even more service on each fiber, we can quadruple FT Series G capacity by upgrading the system to operate at a line rate of 1.7 Gb/s. To each TMA in the 417-Mb/s system, we add three more TMAs and then multiplex their signals up to a line rate of 1.7 Gb/s. Thus, each optical line carries 36 DS3 channels, which is equivalent to 24,192 telephone channels. A fully equipped FT Series G system that operates at 1.7 Gb/s has a capacity of 169,344 protected telephone channels. The TMAs are mounted separately in bays (as photograph b shows) when an upgrade to 1.7 Gb/s is anticipated. Otherwise, they can be mounted together in a bay. Another important aspect of this upgrade capability is that it is accomplished with no decrease in the maximum repeater spacing.

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