L5 System:

Overall Description and System Design

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The L5 Coaxial-Carrier Transmission System is a new solid-state broadband system designed to transmit 10,800 long-haul message channels on standard ⅜-inch (9.5-mm) coaxial cable. Alternatively, high-speed digital signals may be transmitted in selected mastergroups. This paper contains an overall system description and describes in detail system design considerations such as the transmission plan, frequency allocation, and 4000-mile noise performance. Also considered are the significant properties of the coaxial medium, the ways they affect the hierarchy of equalizers traditionally found in long-haul coaxial systems, and the manner in which the several levels of equalization relate to each other and to the fundamental transmission phenomena within the system.

I. INTRODUCTION

During the last 30 years, long-haul transmission facilities have been rapidly expanded to meet the increasing need for both voice and data transmission, and it is expected that rapid growth will continue in the 1970's although possibly at a slower rate than the 15 percent per year which typified the late 1960's. Thus, during this period there has continued to be a need for new systems providing increased message capacity at lower cost to supplement the systems already available in the long-haul plant. As can be seen in Table I, the L5 Coaxial-Carrier Transmission System is the latest in a family of coaxial transmission systems developed to date.[*]

It is evident that the newer coaxial systems have achieved increased capacity because of better utilization of the transmission medium (i.e.,

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[*] The sheath capacities listed in Table I are the ones most commonly associated with each of the systems. The initial L3 application, in 1953, was actually on Coax-8 (i.e., a cable which includes eight coaxials) with a total sheath capacity of 5580 circuits on three working pairs, with one pair reserved for protection.

Table I — Some features of L-type systems

	L1	L3	L4	L5
First service	1941	1953	1967	1974
Technology	Tubes	Tubes	Transistors	Transistors and HIC's
Repeater spacing (miles)	8	4	2	1
Channels per pair	600	1,860	3,600	10,800
Total channels/sheath	1,800	9,300	32,400	108,000
Noise objective (dBrnc0)	44	44	40	40

wider bandwidth) and because of an increase in the number of coaxials incorporated within the sheath. An important characteristic of such long-haul systems is the dominant effect which the installed cost of the transmission medium has on the overall cost. By providing triple the message capacity on L5 as compared to L4, for example, the cost of a message-circuit mile on L5 is substantially less than that of a message-circuit mile on L4, even though the number of repeater stations is doubled and the electronics required is of wider bandwidth and of increased sophistication. In addition, the older L-carrier systems use the same transmission medium, and it is possible to convert many existing L1, L3, or L4 routes to L5 by adding the required number of new repeater sites to the existing sites of the earlier system. In this manner, increased message capacity can be obtained at an incremental cost that is even more attractive than on a new installation.

As noted in Table I, the L5 coaxial system provides 10,800 toll-grade quality message channels (on a pair of 0.375-inch disc-insulated coaxial cables). In a Coax-22 cable configuration, the resultant total channel capacity is 108,000 channels per cable sheath when a 1:10 protection strategy is employed. The increase in the bandwidth of the system required for this capacity is made possible in part by setting the nominal repeater spacing at 1 mile and in part by several significant technological advances in such areas as repeater, network, and device design.[1-3]

The L5 system includes fixed gain "basic" repeaters at 1-mile nominal intervals, adaptive "regulating" repeaters at 7-mile maximum intervals, adjustable gain "equalizing" repeaters at 38-mile maximum intervals, and power-feed main station repeaters at 75-mile maximum intervals.[4] Line protection switching is provided on a 1-for-10 basis at maximum intervals of 150 miles.[5]

The adjustable equalization of the L5 repeatered line is partially manual and partially automatic. Manually adjusted equalizers compensate for the transmission deviations, which are essentially time-invariant. These equalizers are adjusted to minimize the mean-squared error of the broadband channel upon initial installation, and any subsequent readjustments are normally done out of service. The use of out-of-service, mean-squared-error adjustment procedures permits a substantial improvement in the transmission quality for a particular array of adjustable equalizers.

Automatic equalizers compensate for the time-variant transmission deviations. These equalizers are located in each regulating, equalizing, and main station repeater and fall into two categories. The automatic equalizers for the cable-temperature effect are located in each of these repeaters and utilize both open-loop regulating circuits, which detect the resistance of a locally buried thermistor, and closed-loop regulating circuits, which detect the level of a full-time line pilot. The automatic equalizers for the repeater-temperature effect and the regulating repeater tracking error are located only in the receiving main stations and utilize closed-loop regulating circuits equipped with "memory," which detect the levels of four full-time line pilots.

Provisions are included at appropriate main stations for adding, dropping, or branching any jumbogroup (3600 channels) at line frequency.[6] "Dropping" involves connection to the jumbogroup multiplex (JMX), a new frequency-division multiplex (FDM) terminal designed for L5, which translates up to three basic jumbogroups (0.564 to 17.548 MHz) to appropriate line frequency assignments between 3.124 and 60.556 MHz.[7] "Branching" involves connection, at line frequency, to or from another L5 facility. "Adding" involves the addition to an L5 line of circuits originating from the JMX. The mastergroups of a basic jumbogroup are administered much like the mastergroups of an L4 signal. The basic jumbogroup can consist of any available combination of analog and digital mastergroup signals. When frequency assignments permit, direct connection with other facilities is made possible by connecting all mastergroups to the JMX via a basic jumbogroup trunk bay (BJGT). This trunk bay permits mastergroups from several different sources, such as mastergroup multiplex (MMX-2), L-carrier mastergroup digital (LMD) terminals, and radio systems, to be combined into a basic jumbogroup.[6] The carrier generation within the JMX requires reference frequencies of an accuracy heretofore unavailable in the Bell System and consequently

a jumbogroup frequency supply (JFS) is included at all JMX locations for this purpose.[8]

At selected main stations, an L5 transmission surveillance center (TSC) will be utilized to centralize and partially automate the surveillance and fault location of several hundred miles of repeatered line and associated main station and multiplex equipment.[9] In the initial L5 installation between Lillyville, Pa., and Hillsboro, Mo., a single TSC serves these functions for 664 miles of "backbone" route Coax-22, and 151 miles of "sideleg" Coax-12.

II. GENERAL FEATURES OF THE L5 SYSTEM

All long-haul coaxial systems share the common objective of toll-grade signal-to-noise quality in a 4000-mile circuit. In the L5 system, this involves equalization of over 100,000 dB of cable loss at the uppermost message frequencies and almost 132,000 dB at the uppermost "controlled" frequencies near 70 MHz. Equalization of this loss is accomplished with a combination of wideband circuits, all of which must be low in noise, highly linear, and extremely stable. It is in the achievement of the 4000-mile transmission objective that the familiar coaxial system hierarchy of increasingly complex repeaters evolves. Among the general features of the system, the frequency allocation will be considered first. Although many different factors must usually be considered during the specification of a frequency allocation, only a few can be reviewed here.

2.1 Frequency allocation

The controlling consideration in establishing the frequency allocation is the overall bandwidth involved—both in terms of hertz of bandwidth and in terms of the ratio of uppermost to lowermost frequencies to be used—which appears to be consistent with the state of the art at the time, or within the evolutionary lifetime of the system development. An important and relevant experience of previous coaxial-systems development has shown the difficulty and expense of simultaneously controlling the transmission characteristic at the highest and lowest frequencies of a spectrum that spans a frequency range of as much as five to six octaves. Realizable transformers, inductors, and capacitors are in most cases far from ideal components, and parasitic effects become especially troublesome when the frequency range is more than a few octaves. As the system bandwidth approaches five octaves or so, parasitic effects frequently become dominant. Thus, for a given band-

width, there may be significant advantages to raising, within reasonable limits, the lowest frequency requiring careful control.

Compatibility with the existing FDM hierarchy is another relevant factor and, in the case at hand, the basic building block was taken to be the six-mastergroup assembly formed in accordance with the L4 transmission plan. The six mastergroups are arranged between 0.564 and 17.548 MHz and are designated the "basic jumbogroup."

A basic system objective was the transmission of at least three times the L4 message capacity of a single jumbogroup. The assignment of the jumbogroup line frequencies and the spacing between the jumbogroups depends mainly on the bandwidth considerations already discussed and the types of signals and signal administration procedures planned for the system. In L5, the capability to select any jumbogroup from the line spectrum *at line frequency* ("branching and dropping") was a basic system objective. Questions relating to the design of appropriate bandpass and band-stop filters substantially affect the guard spacing required between jumbogroups. In addition, at the time that it was necessary to make the frequency allocation decisions, the ability to displace an entire analog jumbogroup with a high-speed digital signal was also a basic objective.

The frequency allocation of the L5 system is shown in Fig. 1, with six mastergroups, each containing 600 message channels, making up the basic jumbogroup. In some cases, a mastergroup in the L5 line spectrum will transmit a 13.29-megabits-per-second digital signal by means of the L-carrier mastergroup digital (LMD) terminal,[10] a digital repeater spaced at maximum intervals of 300 miles. These digital channels will be used to carry a variety of digital signals including wideband data, DDS, and digitized *Picturephone*® signals.

The regions around 1.59 and 68.65 MHz are used to transmit fault-locating signals which in turn are used to remotely locate repeater faults from a centralized location equipped with an L5 transmission surveillance center.

The region around 68.78 MHz is used to transmit signals required by the line-protection-switching system (LPSS-3) for interstation communication, and control and verification of LPSS operation.

Pilots are transmitted below, between, and above the jumbogroups to control the L5 automatic equalizers. The automatic equalizers for the cable-temperature effect, located in the regulating repeaters, are controlled by the incoming level of the 42.880-MHz pilot (which is often referred to as the "temperature pilot"). The automatic equalizer
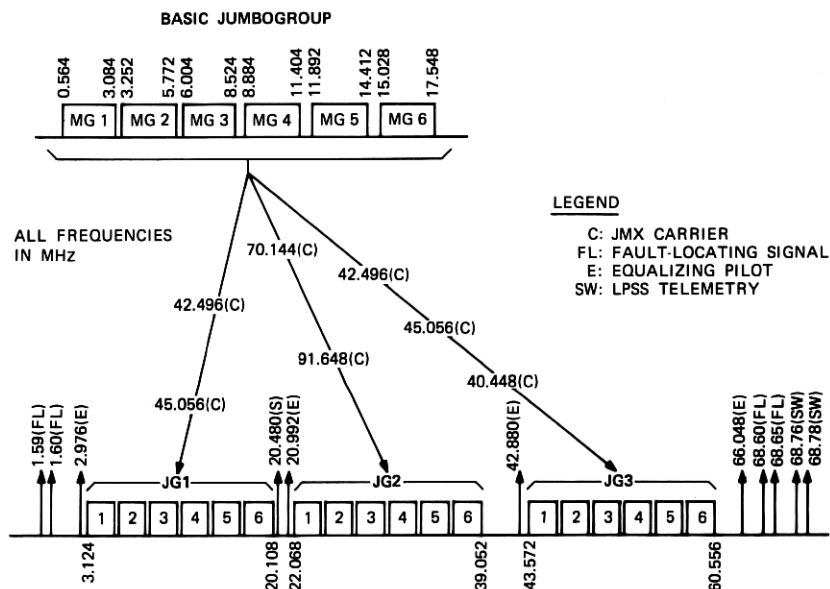
Fig. 1—L5 frequency allocation. The basic jumbogroup shown is equivalent to the L4 line spectrum. The carrier frequencies indicated are those used to translate the basic jumbogroup to the L5 line frequency assignment.

for the repeater-temperature effect and the regulating repeater tracking error, located in receiving main stations and designated the E3 equalizer, is controlled by the incoming levels of all four pilots.

After the establishment of at least an approximate frequency allocation, the central concept in the design of the coaxial system becomes the equalization of the 4000-mile cable loss. Furthermore, it must be done in such a way that the residual transmission deviations are less than 0.01 percent of the top channel cable loss, while accumulated noise from all sources, including associated multiplex, must satisfy the long-haul noise objective of 40 dBrnc0. The general features of the system layout selected to meet these goals are described next.

2.2 System layout

The most general features of a repeatered-line layout in long-haul-coaxial systems depend mainly on power-feeding techniques, equalization strategy, reliability requirements, and convertibility of older systems. The equipment providing power for the remote repeaters, the fine-grained equalization of transmission, and the automatic line-protection

switching will generally be of such size and sophistication as to require a station environment as opposed to the manholes that are suitable for the simpler repeaters. The cost of these main stations is many times that of a manhole, and it is essential that the number of such stations be minimized for system costs to be competitive with alternative ways of providing the circuits.

The power-feed configuration maximizing the length of the power span for a given voltage is the double-ended connection shown in Fig. 2.

The L5 line power supplies provide a nominal 0.91 A dc via the center conductors of the coaxial cables for powering up to 75 miles of remote line repeaters. This is a convenient submultiple of the L4 power span length and requires a maximum line voltage of only ± 1150 V, with the result that physical designs of high reliability should be readily achievable, and corona "popping" in the installed system should be minimal.

The basic layout is affected by the equalization strategy mainly by the effect the latter has on repeater signal loading and the extent of signal level misalignment that must be accepted by the line repeaters. The L5 strategy in most cases uses pre- and postequalization in equal parts and, as a result, repeater load requirements can be reduced for a given transmission deviation from nominal or, for a fixed repeater load capacity, the permissible distance between equalizers can be increased, since the magnitude of the transmission deviation is usually
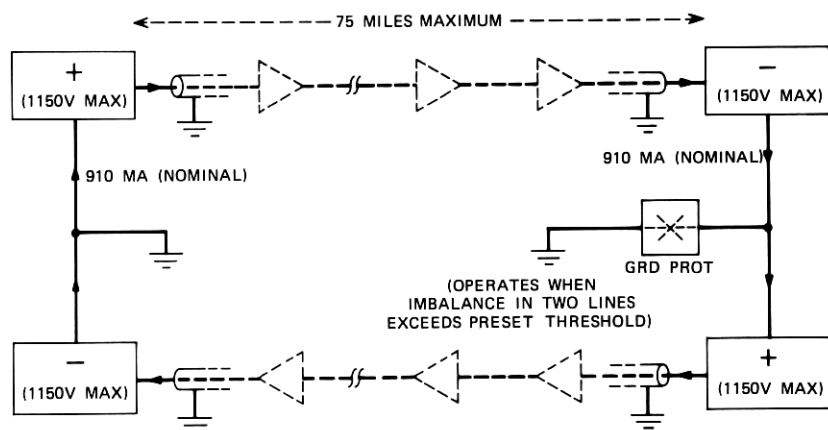

Fig. 2—Simplified diagram of line power feed. Plus or minus voltage is developed by dc-dc converters and combined with message in power separation filters prior to application to coaxial line.

proportional to distance. Finally, when the misalignment is contained to within about ±5 dB, it can be shown that this approach achieves optimum signal-to-noise ratio in both second- and third-order inter-modulation-limited systems.[11] Figure 3 shows the signal-to-thermal noise penalties associated with single-ended equalization, at either the receiver or the transmitter only, and with equal parts of pre- and postequalization.

Finally, a relatively simple adjustable equalizer is included in the midspan manhole repeater so that considerations of equalization and load capacity do not entirely determine the main station interval. The midspan equalizer provides coarse adjustment of signal levels as they traverse the power feed span, and not the fine-grain compensation of transmission deviations, which is accomplished only at the main stations.

Pre- and postequalization is applied throughout the L5 repeatered line except for the automatic equalization of the repeater-temperature effect, the controlling considerations in this case being simplification of system operation and reduction of system complexity. The repeater-temperature effect is equalized only in the receiving portion of main station repeaters, which are up to 75 miles apart.

Reliability affects system layout, since the reliability of the system electronics determines the length of the protection-switching span and
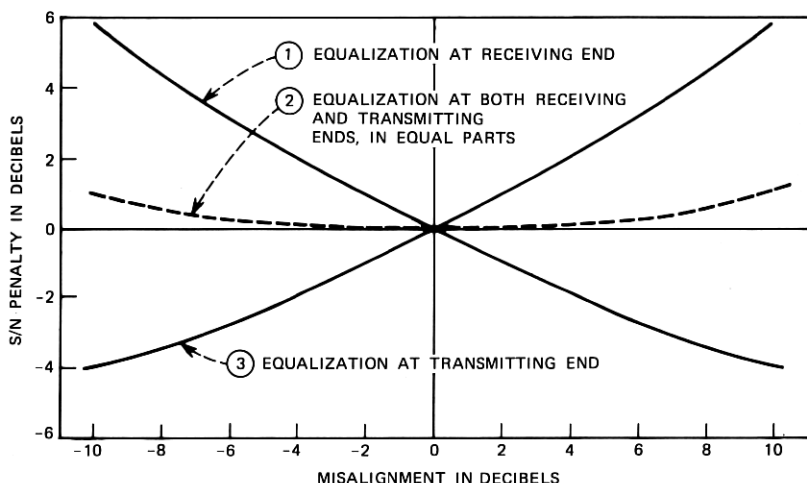

Fig. 3—Signal-to-thermal noise penalties resulting from signal misalignment. For misalignment less than about ±5 dB, pre- and postequalization in equal parts (curve 2) also results in negligible penalties in second- and third-order intermodulation noise (not shown).
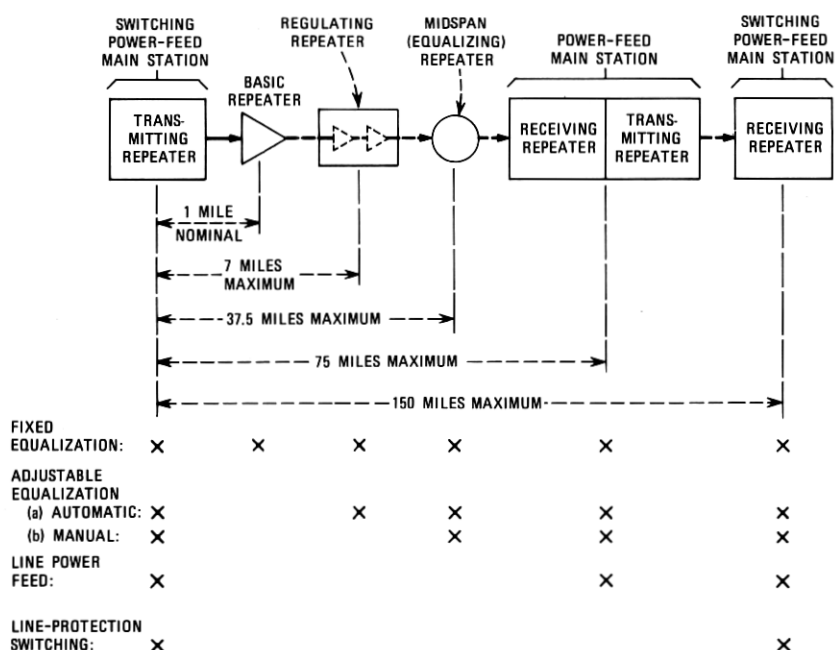
Fig. 4—Main features of an L5 switching span.

SWITCHING POWER-FEED MAIN STATION — TRANSMITTING REPEATER
BASIC REPEATER
REGULATING REPEATER
MIDSPAN (EQUALIZING) REPEATER
POWER-FEED MAIN STATION — RECEIVING REPEATER / TRANSMITTING REPEATER
SWITCHING POWER-FEED MAIN STATION — RECEIVING REPEATER

1 MILE NOMINAL
7 MILES MAXIMUM
37.5 MILES MAXIMUM
75 MILES MAXIMUM
150 MILES MAXIMUM

	Transmitting repeater	Basic repeater	Regulating repeater	Midspan (equalizing) repeater	Power-feed main station	Switching power-feed main station (receiving)
FIXED EQUALIZATION:	X	X	X	X	X	X
ADJUSTABLE EQUALIZATION (a) AUTOMATIC:	X		X	X	X	X
(b) MANUAL:	X			X	X	X
LINE POWER FEED:	X				X	X
LINE-PROTECTION SWITCHING:	X					X

the number of lines required as standby for any given availability objective to be achieved. The predicted reliability of the L5 line repeaters permits up to two power-feed spans to be traversed before automatic line-protection switching is required, and then on a 1-for-10 basis. In the context of the repeatered line, the basic building block of the system is the switching span and, in the absence of signal administration needs (dropping, branching, etc.), such spans as are shown in Fig. 4 are connected in tandem until the distance between terminal stations is bridged.

In addition to the provision of repeatered-line power, fine-grain equalization, and (sometimes) line-protection switching, other important functions are carried out at the different types of L5 main stations, and, depending on the particular features required of main stations, they fall into one of three categories. In order of decreasing complexity they are:

(*i*) Terminal station/terminal main station (TS/TMS).
(*ii*) Switching power feed main station (SPFMS).
(*iii*) Power feed main station (PFMS).

The functions performed at these stations which are directly related to the repeatered line are alike. The differences among them are in the signal and pilot administration (line connecting) functions, the line-protection switching, the transmission-surveillance capabilities, and the multiplexing and related signal-processing functions.[6] Some main station and repeater functions are summarized in Fig. 4, and some possible terminal interconnections for jumbogroup administration are shown in Fig. 5.

2.3 System installation, operation, and maintenance

A basic objective in the design of the L5 system was to achieve a system requiring a minimum of day-to-day routine involvement of craftspeople. The L5 main stations, as well as the repeatered line, will generally be operated without personnel present. This has been made possible in part by developing equalization procedures that should require activity only rarely, and in part through the implementation of centralized alarm, surveillance, and fault-locating techniques. The layout of the initial L5 commercial installation between Lillyville, Pa., and Hillsboro, Mo., is shown in Fig. 6 and, for purposes of the following discussion of system organization and administration, is treated as typical.

2.3.1 Installation and maintenance

Installation of the L5 repeatered line is accomplished by telephone company personnel and is controlled and supervised at "maintenance centers." Six such maintenance centers are shown in Fig. 6; the four at Danville, Xenia, Morgantown, and Noble have responsibility for all but the 30 repeater sections near Lillyville and the 14 repeater sections near Hillsboro. Those four stations are consequently each responsible, on the average, for the installation and maintenance of nearly 200 miles of repeatered line which, when fully equipped, will include approximately 4000 line repeaters.

Upon being received from the factory, every L5 repeater is carefully tested at one maintenance center before installation along the repeatered line. The tests made involve primarily transmission measurements that are executed, on site, by a computer-operated transmission measuring set and associated test stand. A hard copy of the test results is produced during the process and, in the case of an acceptable repeater, is retained in the maintenance center as part of the permanent history file on that repeater. Regulating repeaters and fault-locating oscillators are among system components requiring on-site adjustment
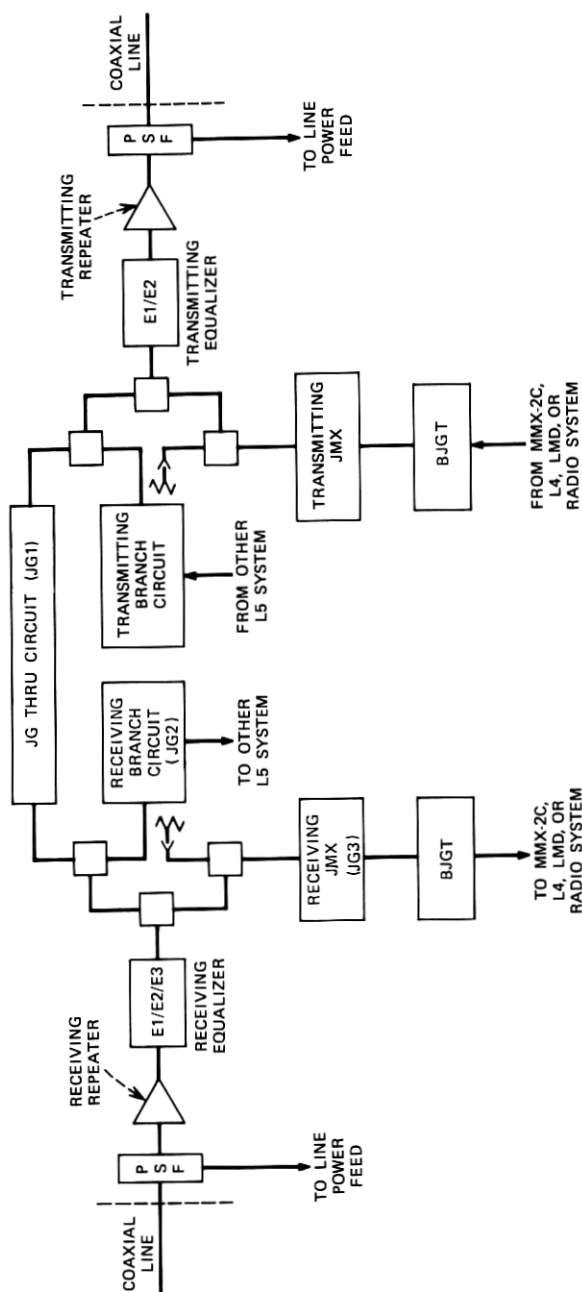
Fig. 5—Jumbogroup administration. In the hypothetical case shown, JG1 is through-connected at line frequency and JG2 is branched on to another L5 system also at line frequency. JG3 is dropped via JMX and the BJGT to basic jumbogroup for interconnection with MMX-2, L4, a radio system, or a combination thereof.
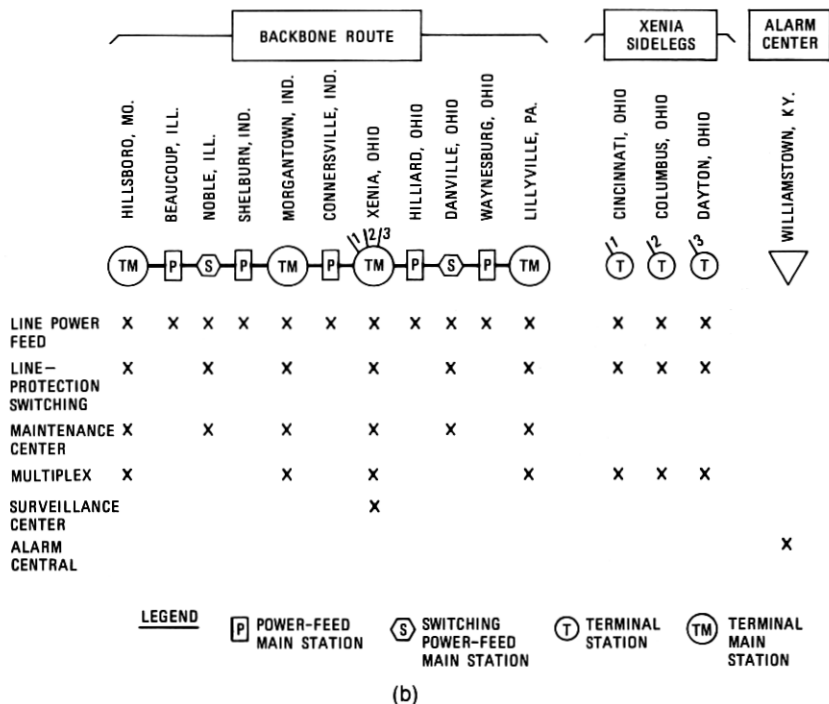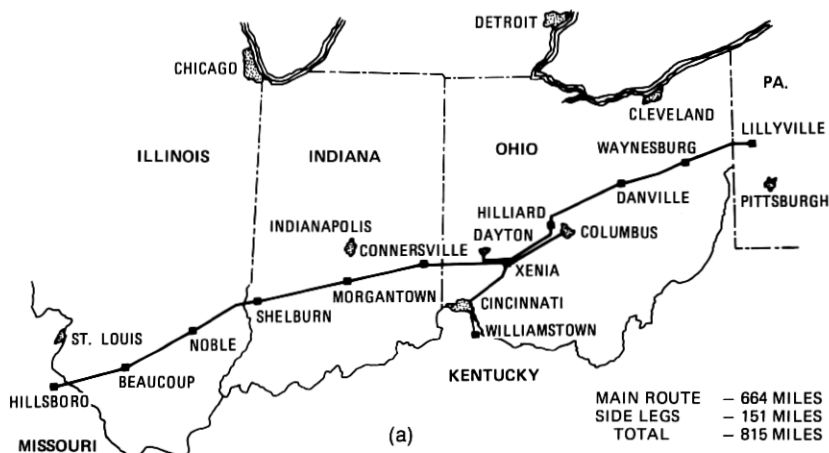
Fig. 6—(a) Geographical layout of initial L5 commercial installation between Lillyville, Pa., and Hillsboro, Mo. (b) Administrative layout of Lillyville-Hillsboro route.

in accordance with the particular repeater station to which they are assigned, and those adjustments are normally made utilizing the same test setups.

Installation of the L5 main station equipment is usually done by Western Electric installation personnel and, prior to turnover of the equipment to the telephone company, a variety of transmission, noise, and operational tests is usually necessary. In most cases, these tests utilize the same kind of test equipment required by the telephone company to install, maintain, and operate the system.

After the testing and installation of the repeaters and fault-locating oscillators have been completed between a pair of power-feeding points (such as Lillyville and Waynesburg in Fig. 6), and after the main station equipment has been installed and tested, power is applied by operating the line-power-feed dc-dc converters at both ends of the line. The converters at each end are adjusted to share equally the load of the intervening repeatered line (except in the case of very short power spans, which can be powered by converters at one end only). With power applied to the line, a detailed step-by-step process, known as the L5 line acceptance procedure and appropriately documented, is executed, which permits the systematic identification and elimination of any system faults that may have escaped detection during the earlier testing of the individual repeaters and cable sections. In addition, such engineering or operational errors as incorrect line-build-out specification, incorrect fault-locating oscillator adjustment, or improper pre-regulator settings can, with a combination of engineering and on-site analysis, readily be detected. The line acceptance procedure flows from a detection of the gross faults that may have existed, through a regulator-by-regulator pilot level measurement sequence, to the measurement, evaluation, and equalization of the channel between main stations, and ultimately to the noise loading of the tandem power-feed spans making up a protection-switching span (such as between Lillyville and Danville in Fig. 6). Upon completion of this procedure, the repeatered line is ready for the next level of system testing, which would consist of such procedures as exercise and validation of the protection-switching system, including tandem operation (such as from Lillyville-to-Danville-to-Xenia in Fig. 6) and multiplex-to-multiplex measurements and evaluation (such as between Lillyville and Xenia).

2.3.2 System alarms

A wide variety of status and alarm indications has been made available in the L5 system design to provide for complete and ready

remote verification of system health as well as diagnosis of system troubles when they occur. Status indications are provided for such operating parameters as the dynamic equalizer range setting and the condition of the protection-switching system, while alarm indications are developed based on the power level of any line or jmx pilot, the condition of any fuse, and a variety of other parameters. These alarm and status indications are transferred to a central alarm station which, in Fig. 6, is located at Williamstown, Ky., off the L5 route. This station is part of the E2 Status Reporting and Control System and, in the following discussion, references to E2 will be to this system, not to the E2 equalizer that is an integral part of the L5 system. Transmission between the L5 stations and the E2 central station takes place over a data network which is a four-wire private line, meeting requirements similar to those of a standard voice-band data service. (In the case of the initial L5 installation, the data facility is located internal to the co-axial cable, utilizing two of the loaded 19-gauge pairs, as far as Cincinnati, and utilizes an external private line circuit between Cincinnati and Williamstown.) Each L5 main station is equipped with at least one E2 "remote unit," which provides the interface between the L5 system alarms and the E2 data facility. The larger L5 stations, such as Xenia and Morgantown on the initial route, require two E2 remote units, because of the quantity of equipment to be located there. The total load on the Williamstown E2 central is 16 remote units, the upper limit for a "manual" E2 central on a single data network.

In its normal operating mode, the E2 central sequentially interrogates (alarm polls) each remote unit for its alarm poll response. When all remote units have been polled, the process is successively repeated. A manual operation at the central or a demand by the L5 transmission surveillance system (tss) for use of the data facility will interrupt this otherwise automatic and repetitive alarm polling. The manual operations at the central include calling up a particular station display for a detailed alarm report as well as controlling such L5 system operations as effecting a line switch or operating the line-feed converters.

2.3.3 Surveillance and fault location

The surveillance and fault-location features of the system are described in detail in Ref. 9, and will be touched on here only briefly. The addition of a remote call-up feature to the E2 Status and Alarm Reporting System described above permits the L5 tss to time-share the E2 data facility and the multiple-address capability of the E2 central. The tss of the initial L5 route has a single transmission-

surveillance center (TSC), located at Xenia. Equipped with a mini-computer central processor, and loaded with appropriate data-base, operating-system, and applications programs, that TSC controls the fault-location and surveillance processes for all the repeaters and main stations in the initial system. (The total mileage represented by Fig. 6 is approximately 815 miles. When fully equipped, the equipment "domain" of the TSC at Xenia will include over 17,000 line repeaters and more than 250 transmit-receive bays, as well as associated multiplex.) Virtually all the periodic maintenance measurements planned for the system will be carried out at the TSC and, by supplying a full duplex data circuit between Xenia and Williamstown, operation of the TSC can be transferred to Williamstown during Xenia's unmanned intervals.

III. DESIGN OBJECTIVES AND SIGNAL-TO-NOISE ANALYSIS

3.1 Repeater design objectives

The transmission plan of an analog coaxial system is determined by adjusting the bandwidth, repeater spacing, and signal transmission levels so that prescribed channel objectives are realized over the life of the system. To transmit over a particular bandwidth on a specified cable, the repeater spacing is determined by the available gain, noise figure, load-carrying capacity and linearity of the repeater, and the margins required to allow for cable and repeater variations resulting from aging, temperature changes, and manufacturing limits.

Table II illustrates how the basic repeater noise, load capacity, and linearity design objectives became progressively more stringent as coaxial-system design proceeded from L3 through L5. In comparing

Table II — Design objectives for L-type repeaters

System Data	L3	L4	L5
Top frequency (MHz)	8.3	17.5	60.6
Repeater performance, referred to top channel:			
Noise figure (dB)	11	6.5	5.5
Load capacity (dBm)	16	21	24
Nonlinearity			
Second order (dB)	−61	−70	−70
Third order (dB)	−96	−100	−110*
Insertion gain (dB)	44	33	31
Transmission level (dB)	−11	−14.2	−13.6

* This requirement applies only with the use of the phase-shaping networks described in Section 3.2.

the repeater design parameters of the table, it is important to note that the required noise, load capacity, and linearity improvements from L3 through L5 are achieved at progressively higher top channel frequencies. Table II shows, for example, that operating at one-half the L4 repeater spacing and more than three times the L4 top channel frequency, the L5 basic repeater requires a 1-dB better noise figure, 3-dB more load capacity, and 10-dB better third-order nonlinearity than the L4 basic repeater, with all parameters referred to their respective top channel frequencies. Top channel insertion gain is slightly lower in the L5 repeater despite the higher top transmitted frequency because of the 2:1 reduction in repeater spacing.

3.2 Signal-to-noise analysis

The L5 system signal-to-noise design objective is based on meeting a 4000-mile per channel noise objective of 40 dBrnc0. The 40-dBrnc0 total is allocated as 39.4 dBrnc0 to the high-frequency line and 31.5 dBrnc0 to the terminals (Fig. 7 shows how the 31.5 dBrnc0 terminal allowance relates to a possible multiplex deployment). In the signal-to-noise design of the system, high-frequency line transmission levels are shaped with frequency to realize noise performance in every channel as nearly equal as possible. In L5, second-order modulation
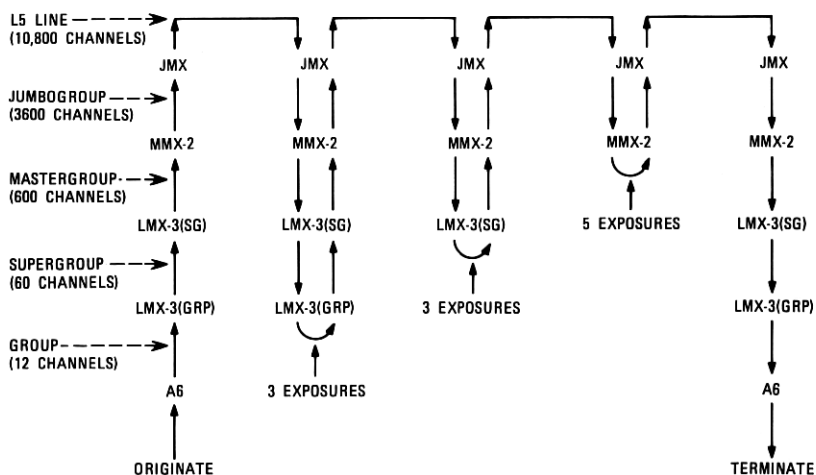

Fig. 7—Possible multiplex terminal deployment in a long-haul interconnection. This example includes 11 intermediate multiplex operations between the originating and terminating stations, which is well above the number typically encountered.

noise is the controlling modulation contributor because of the use of the phase-shaping networks discussed below, which serve to reduce the third-order intermodulation distortion to a relatively insignificant level. In L5, application of signal level shaping techniques results in the transmission levels shown in Fig. 8a and in the predicted zero level noise shown in Fig. 8b. The curve labeled "Total" in Fig. 8b is the predicted noise under nominal conditions. The uppermost curve, labeled "Total (with allowances)," is the predicted noise performance including penalties for misalignment, misequalization, and the like. As can be seen, the average noise over all channels is predicted to be 39.7 dBrnc0 under nominal conditions. The use of frequency frogging of the jumbogroups and mastergroups will tend to cause the typical 4000-mile L5 channel to approach that average value in noise performance. In addition, measurements on the L5 field trial and first commercial installations indicate close agreement with 4000-mile predicted noise proportioned to the appropriate test system length. A controlling factor in the determination of the allowable second- and third-order modulation coefficients listed in Table II is the use of repeatered line phase-shaping networks in each L5 regulating repeater. Such networks are used to produce a significantly less linear repeatered line phase-frequency characteristic, resulting in reduced correlation of third-order $(A + B - C)$-type product addition from repeater to repeater. In the absence of phase-shaping, such product addition would occur on a nearly in-phase or voltage-addition basis, with the repeater-to-repeater terms approaching $20 \log N$, where N is the number of tandem line repeaters.*

In the presence of the phase-shaping networks, such as those used in L5, substantially lower correlation of $(A + B - C)$ product addition results. For the L5 6-mile regulating-section phase-frequency characteristic shown in the upper curve of Fig. 9, the repeater-to-repeater addition term within a frogging link is approximately $15 \log N$, corresponding to a per-frogging-link $(A + B - C)$-type product reduction of about 15 dB relative to the "no-phase-shaping" values. Thus, in L5, the use of phase shaping reduces third-order intermodulation noise to relatively insignificant values, and the system is second-order modulation and thermal-noise limited.

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* Product addition according to a particular law occurs over "frogging" link intervals of up to 800 miles. Because of the randomizing effect on product and source frequencies produced by frogging, random or power addition is assumed to occur from frogging link to frogging link for all modulation product types.
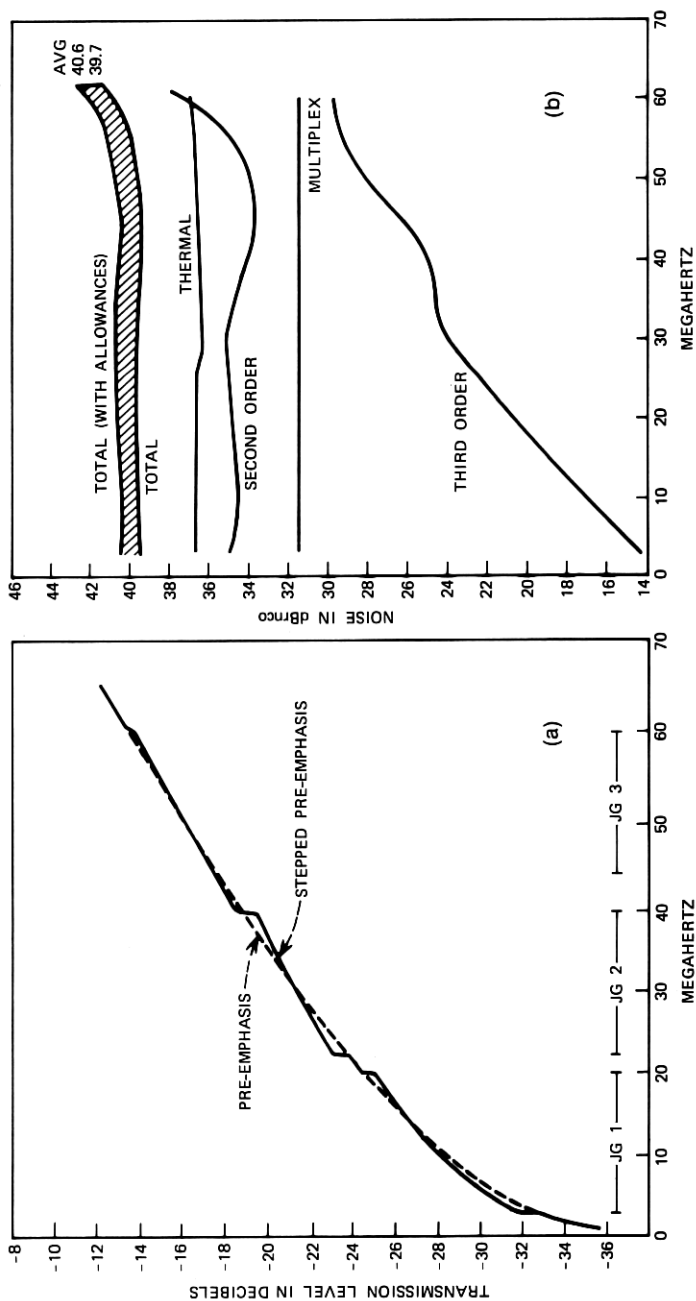
Fig. 8—(a) Repeater output transmission levels. The discontinuities in the TL shown result from using a stepped approximation to the optimum (smooth) preemphasis curve, derived by transmitting JG2 1.7 dB hotter than JG1 and JG3 1.8 dB hotter than JG2 at the JMX output. (b) Predicted zero level noise for 4000-mile L5 system. The prediction is based on extensive individual repeater and transmit-receive bay measurements, and has been confirmed by noise loading measurements made on lengths of the initial system up to 750 miles long.
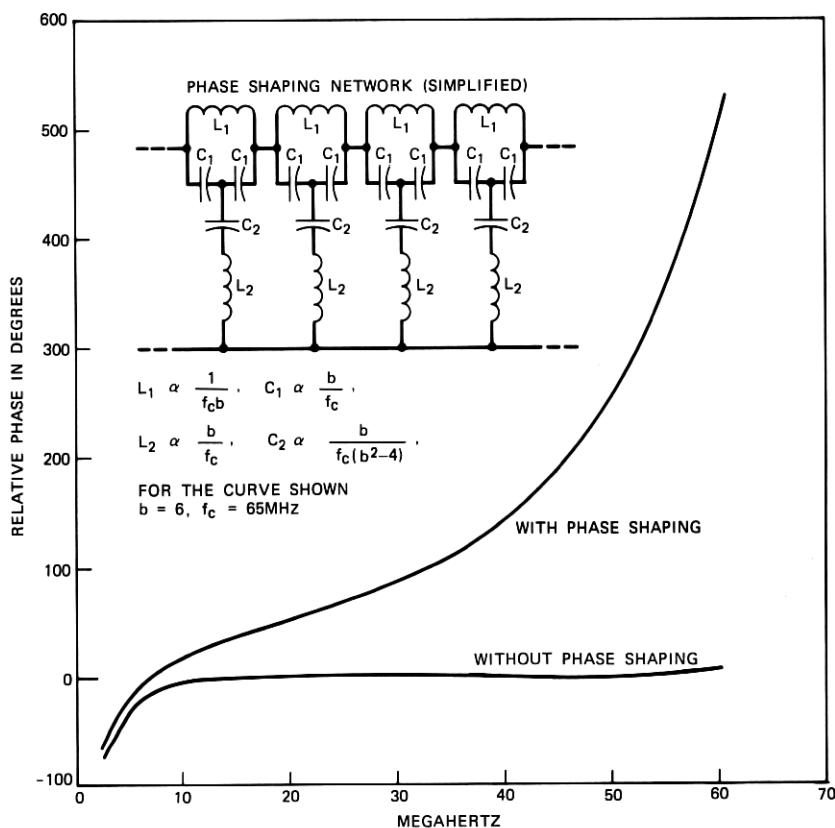
Fig. 9—Relative phase (linear component subtracted) of L5 regulating section—with and without phase-shaping networks in regulating repeater. The parameter b is a measure of the "stiffness" of the ϕ-f characteristic of the networks, and f_c is the frequency at which the phase shift of each of the four sections is 180 degrees.

IV. REPEATERED LINE DESIGN

As mentioned previously, the design of the repeatered line of a long-haul coaxial system centers largely about the equalization of the 4000-mile cable loss, and the cable used in the L5 system and its transmission characteristics are described next.

4.1 Coaxial medium

The typical L5 cable (new installation) will be a Coax-22 and will contain 22 disc-insulated coaxials and 42 polyethylene-insulated

conductor pairs. (A cutaway view of a Coax-20 is shown in Fig. 10.) The paired conductors in these cables are used for support systems such as order wire, fault location, and air-pressure telemetry.

The loss characteristic of the cable over the band of interest in L5 can be approximated by

$$\alpha(f, T) = 3.9002 \left(1 + \frac{0.0062}{\sqrt{f}} \right) \sqrt{f} + 0.0047f$$
$$+ 0.0043(T - T_o)\sqrt{f} \quad \text{dB/mile}, \quad (1)$$

where f is in MHz, T in °F, and $T_o = 55°F$.

The first term of the right-hand side is a result of the resistance loss of the copper conductors and, at L5 frequencies, owing to skin effect, this loss is proportional to the square root of frequency. The second term reflects the dissipation in the polyethylene disc spacers that maintain the relative positions of the inner and outer conductors, and it increases linearly with frequency. (This term is often called the "power factor" term.) The third term reflects the temperature dependence of the copper resistivity, and is also proportional to the square root of frequency.

Although the cable loss representation in eq. (1) is perfectly adequate over the transmission band of L5 and its predecessors, distortions in the cable loss will be encountered as system bandwidths are extended further, which in some cases may limit those bandwidths. For example, structural return loss (SRL) spikes are encountered, which result from the cable-stranding operation during manufacture. The strander periodically deforms the coaxials as they precess about the cable core, and, for a fixed stranding lay, the SRL spikes are coherent and result in relatively narrow-band transmission deviations from the behavior predicted by eq. (1). The current lay length for the outer coaxials in Coax-20 (cables having 20 coaxial tubes within the sheath) and Coax-22 is 36 inches $\pm \frac{1}{2}$ inch and results in SRL spikes at 157 ± 2.5 MHz. Other distortions are caused by seam interaction or "back twist," which is also a product of the stranding operation. These occur in the outer coaxials of the Coax-20 and Coax-22 around 170 MHz. The inner units of Coax-20 and -22 (8 in each case) and all the units of Coax-12, since they have shorter lay lengths, exhibit these effects at higher frequencies than those noted for the 36-inch lay length. For the purpose of designing the hierarchy of repeaters and equalizers that make up the repeatered line, the loss described by eq. (1) becomes the basic objective for repeater gain per mile of system, as discussed next.
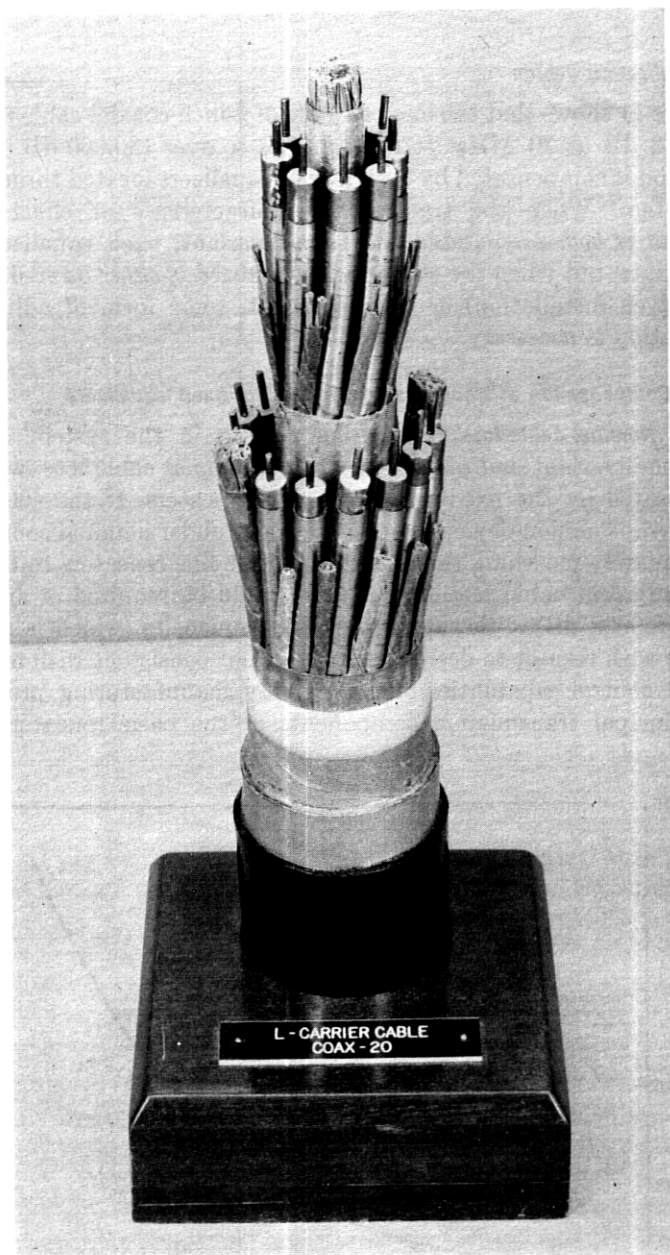
Fig. 10—Coax-20 of serrated seam construction. This cable is the backbone of nearly all existing L4 routes, and includes 52 paper-insulated wire pairs in addition to the 20 coaxials. New L5 construction will normally utilize Coax-22, specifically developed for L5.

4.2 Equalization design

Figure 11 shows that the loss of 1 mile of $\frac{3}{8}$-inch coaxial cable reaches about 33 dB at 70 MHz. It accumulates to over 130,000 dB in 4000 miles, and is compensated by a variety of equalizers located throughout the system. When the transmission characteristic or effect being equalized is *both* predictable *and* time-invariant, fixed equalizers are appropriate, but when the effect to be equalized is *either* unpredictable (in a given installation) *or* time-invariant, some form of adjustable equalization is necessary.

4.2.1 Compensation of transmission effects with fixed equalizers

4.2.1.1 Nominal cable loss. The principal loss in the system that is *both* time-invariant *and* predictable is the nominal cable loss, which is compensated by the fixed-gain basic line repeaters. If the 4000-mile system transmission objective were to be met under nominal conditions by adequately matching the gain of the basic line repeaters to the loss of the adjacent cable section, a match would be required of approximately 0.0008 dB at the uppermost L5 frequencies, which is neither realistic with respect to design complexity nor consistent with measuring and control capabilities of present-day manufacturing processes. The principal transmission components of the basic repeater are a
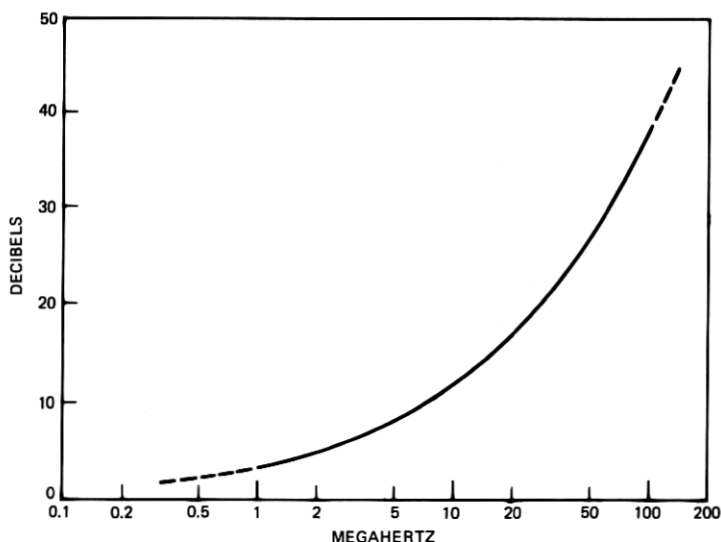

Fig. 11—Nominal loss of 1 mile of standard $\frac{3}{8}$-inch coaxial cable at 55°F.

low-noise preamplifier, a highly linear power amplifier, and an optional artificial line called a line-build-out network (LBO). These and the remaining components of the basic repeater are described in detail in Ref. 1.

4.2.1.2 Deviations from nominal repeater spacing. When the repeaters cannot be installed at the nominal 1-mile intervals, the resultant spacing deviations are compensated for by the abovementioned LBO networks which simulate the loss of a length of the coaxial cable, and are available in 0.1-mile increments from 0.1 to 0.5 mile. Because of obstacles, access problems, or other geographical limitations, it is usually impossible to achieve exactly 1-mile spacing between adjacent repeater sites. In such cases, the line repeaters are assigned one of the available LBO's to increase the loss of shorter cable sections to that of 1 mile of cable. For unusual obstacles such as river crossings, for example, a limited number of long repeater spacings may be permitted by requiring the repeater sections on both sides of the long section to be shorter than nominal. The administrative rules for all these cases are described in detail in engineering documentation available to the telephone company engineer at the time of route layout and route planning.

4.2.1.3 Average design error. In previous coaxial systems, such as L3 and L4, the equalization of the average difference between line repeater gain and cable loss (i.e., the average "design error") has been attempted with families of fixed equalizers called "design deviation equalizers" or simply "deviation equalizers." The functions of such equalizers are, first, to contain the transmitted signal levels at close to nominal values and, second, to enhance, in conjunction with all the other equalizers in the system, the ultimate transmission response of the system. While the first of these can often be guaranteed with relatively high confidence, the enhancement of the equalized transmission response is more difficult to achieve as a product of such equalization strategy.[1] This section discusses some reasons for this and some considerations involved in seeking an optimum overall set of equalizers (fixed plus adjustable).

As mentioned before, the initial design objective for a deviation equalizer is the complement of the average design error of the line repeaters. As used here, this error is the difference, on the average, between the gain of the line repeaters and the loss of the associated nominal length of coaxial cable. Ideally, the basis for computing the average difference would be the universe of all manufactured line

repeaters and cable. In reality, the basis must be the largest sample of each that is available before final manufacturing commitments must be made on the equalizers.

Even if the optimum information were available when desired, network realization limitations leave a residual error requiring further equalization, and when the deviation equalizers consist of a family of several different designs (as in L4, for example) there are several different realization errors. Naturally, the specific errors for different physical models of the "same" network also tend to be different (because of what is usually called the manufacturing deviation). Finally, even if the realizations were ideal, the average design error characteristic of the repeaters used as a basis for the deviation equalizer design will not always be characteristic of the set of repeaters in any particular line section.

The collective impact of these factors is a tendency to introduce "ripples" into the frequency response of the channel. Even though characterized by smaller amplitude deviations than the unrippled deviation, the rippled frequency response can often be more difficult to equalize. Of equal importance, the variations from line to line in the rippled characteristic resulting from the above factors will often be more difficult to track with a selected set of adjustable equalizers than would the line-to-line differences in the unrippled deviation (i.e., that existing before the application of the deviation equalizers).

To the extent that these factors contribute significantly to the ultimate residual error of an equalized channel, the transmission response of that channel would apparently benefit from minimizing the number of different types in the family of networks, and/or minimizing the number of locations at which the deviation equalizers are inserted. The straightforward application of these guidelines leads to a single deviation equalizer design inserted as infrequently (along the repeatered line) as possible, while the most extreme interpretation would lead to *no* deviation equalizers as such, a condition that probably could be achieved only with the addition of relatively costly adjustable equalizer stations, since the signal levels must still be contained within the repeater load capacity as the signal traverses the repeatered line.*

It is possible that the latter might be a desirable solution for a *single* equalizing section, which in L5 will be up to two power-feed spans.

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* The cost of a fully equipped L5 manhole equalizing station in a medium-cost zone is about twice that of a fully equipped regulating repeater station, which would normally be used otherwise.

However, when there is no attempt whatever (such as with deviation equalizers) to reduce the average misalignment over all equalizing sections to a value nearer zero, then all the adjustable equalizers in a long circuit would tend to be set to the same side of their nominal setting. As a result, there would be no tendency whatever to cancel (or randomize) the errors and transmission distortions originating in the equalizers themselves and in their inherent equalizing limitations, and these would accumulate systematically in a long circuit, quite possibly becoming the major source of residual overall transmission deviation. Short of this extreme, a solution based on a single network design and application in a minimum number of locations is attractive from several viewpoints, and such a solution has been incorporated into the L5 design.

The L5 deviation equalizer design provides one-third the total "design error" equalization required by a 66-mile repeatered line (approximate average power span length) in single networks located in the transmitting and receiving main stations and at the midspan equalizing station. The network has been designated the "22X" deviation equalizer, since the design objective is approximately the design error of 22 miles of L5 repeatered line. The particular method used to realize the deviation equalizer design is described in detail in Ref. 1. As described there, the L5 deviation equalizer, while in principle correcting the average design error, is realized in the final design stages using computer optimization routines that interact with the available adjustable equalizers. Figure 12 shows the signal misalignment as a function of distance, per 3 dB of 66-mile correction, employing the 22X approach and assuming uniform accumulation of the misalignment. As far as signal-to-noise penalty is concerned, it can be seen that this arrangement is equivalent to pre- and postequalization, in equal
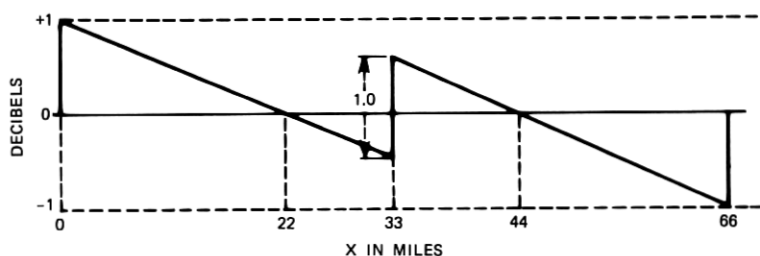

Fig. 12—Equalization of the average design error. The relative signal level is shown for a case involving 3 dB of misalignment in 66 miles; three identical deviation equalizers are placed at the transmitter and the receiver, and midway between.

Table III — Deviation equalizer application rule

X in miles	Power Span of X Miles		
	TRMTG RPTR	MIDSPAN RPTR	RCVG RPTR
55 to 75	Yes	Yes	Yes
33 to 55	Yes	No*	Yes
11 to 33	No	*	Yes
Less than 11	No	*	No

* No midspan equalizing repeater required for $X < 37.5$ miles.

parts, of 44-mile sections having ± 1-dB signal excursion in tandem with 22-mile sections having ± 0.5-dB signal excursion, each section incurring signal-to-noise penalties very near zero (see Fig. 3).

Naturally, administrative rules are required to assist the telephone company engineer in the determination of his 22X equalizer needs. With "quantum steps" of 22 miles of fixed equalization, it is possible to specify the fixed equalization to within $\pm 22/2$ miles of the ideal value, and the application rules specified for L5 are shown in Table III. Note that execution of the tabulated rules should approach compensation, on the average, of the design error in a long (multispan) system that operates at a uniform mean temperature. In so doing, the rules should result in slight over- or undercompensation of the individual equalizing sections which will be of varying lengths. This effect, along with the significant variations in mean cable temperature that normally will be characteristic of long systems, should result in a tendency to randomize the adjustable equalizer settings, thereby mitigating the systematic accumulation of the errors and distortions originating in the adjustable equalizers themselves, and in their inherent equalizing limitations.

4.2.2 Compensation of transmission effects requiring adjustable equalizers

As discussed above, those transmission effects that are *either* time-variant *or* unpredictable (or both) require some form of adjustable equalization. Adjustable equalizers can be automatically or manually adjusted and the process can be carried out either in- or out-of-service, as particular circumstances and considerations warrant. In the case of L5, each of these possible types of equalizer and equalization processes is utilized among the various members of the equalization hierarchy.

4.2.2.1 Cable-temperature effect. The largest time-variant transmission deviation in a coaxial cable system, normally orders of magnitude greater than any other, is the cable-temperature effect, shown in Fig. 13 for 1 mile of ⅜-inch cable and for a 20°F change in cable temperature. Extrapolated to 4000 miles, the temperature dependence depicted here corresponds to about ±3000 dB of loss variation at the uppermost L5 frequencies, uniformly distributed over that distance. In L5, this is corrected at intervals not greater than 7 miles in "regulating repeaters" which, in addition to compensating for the nominal cable loss, provide automatic equalization of the cable-temperature effect. The regulating repeater compensates for the changing cable loss within a "regulating section" which, in typical installations, has an average length of approximately 6 miles.

In addition to the components found in a basic repeater, the major transmission components of the regulating repeater are a pair of adjustable equalizers having the adjustable loss frequency capability shown in Fig. 13 for the cable-temperature effect. The first equalizer operates in a closed-loop feedback mode and postequalizes for a portion of the preceding regulating section. The second equalizer operates in an open-loop mode by sensing the resistance of a thermistor buried in the ground near the cable, thereby pre-equalizing for a portion of the cable-temperature effect of the ensuing regulating section. These two equalizers restrain the maximum level deviations resulting from the
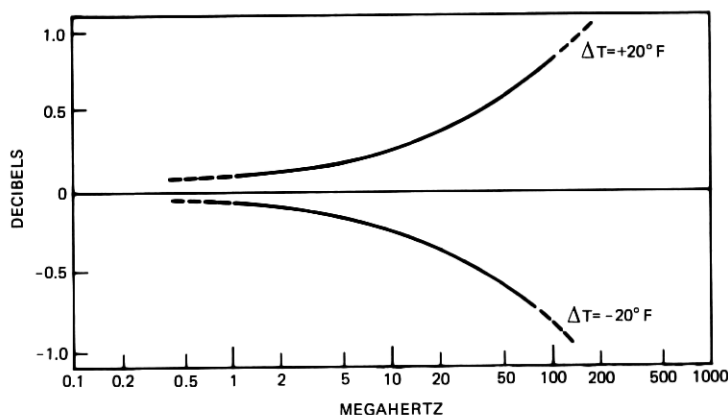

Fig. 13—Effect of changing earth temperature on 1-mile cable loss. The indicated temperature range is only rarely exceeded within the continental U. S. at the cable burial depth of 4 feet.

cable-temperature effect to about ±2.5 dB within a regulating section through the use of the pre- and postequalization method. When the system is properly aligned, the pre-equalizer in one regulating repeater and the postequalizer in the subsequent regulating repeater each compensate for one-half the cable loss variation of the intervening cable section. The remaining components and a more detailed description of the regulating repeater operation are included in Ref. 1.

4.2.2.2 Repeater-temperature effect. The other major time-variant transmission deviation is the repeater-temperature effect. This results from both the regulating repeater tracking error associated with equalizing the cable-temperature effect (a maximum of 0.10 dB per regulating section) and the direct effect of changing temperature on the transmission responses of the various line repeaters (less than 0.02 dB per repeater section). Suitable allowances had to be made in the repeater signal loading requirement to permit this effect to be equalized at the receiving end only of each power-feed span (up to 75 miles long). This is accomplished in the "dynamic equalizer," a cause-associated, adaptive equalizer with memory,* the important characteristics and operational features of which are described in Ref. 1.

4.2.2.3 Statistical manufacturing deviation. The largest time-invariant transmission deviation requiring adjustable equalization is the statistical manufacturing deviation that results from the (usually small) differences in electronic component values within their specified tolerance ranges. Thus, the exact frequency shape of this deviation is not predictable for any given collection of repeaters in a particular installation, although it can be predicted to fall within certain overall limits. In L5, this deviation is compensated by equalizers E1 and E2 which are manually adjustable because the deviation is time-invariant once identified. These equalizers consist of 28 adjustable Bode-type equalizers ("bump" equalizers)—18 in the E2 and 10 in the E1. Both E2 and E1 equalizers are located in the transmitting and receiving main stations, while only the E1 equalizer, mechanically adapted for manhole use, is utilized at the midspan equalizing repeater. The deployment chosen for the equalizing stations is the result of seeking a reasonable balance between the amount of misalignment that would have to be tolerated by the line repeaters, with resultant signal-to-noise penalties and effects on repeater power requirements,

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* The memory in the dynamic equalizer permits the transmission response of the equalizer to remain unchanged if any equalizing pilots are lost.

and the proliferation of the relatively complex (and relatively costly) equalizing repeaters that would otherwise be required to keep the misalignment and associated signal-to-noise penalties small.

To estimate the static misalignments to be encountered, it is necessary to know some transmission properties of the repeaters which, at the outset of a system design, either are in the form of repeater requirements or, at times, are based on previous experiences with similar transmission components. In the case of the L5 design, a requirement was imposed on the line repeaters that (i) the average gain of the repeaters match the nominal cable loss within ± 0.1 dB and (ii) the spread among the gains of all manufactured repeaters would be less than ± 0.1 dB with respect to that average. This, in combination with the deviation equalizer strategy described in the preceding section, made it possible to specify and design a single midspan (between power-feed stations) adjustable equalizer having both adequate range and adequate margin (against the possibility, for example, that the repeater transmission requirements turned out to be unrealistic, or too costly to achieve, and might thus have been relaxed somewhat). As mentioned earlier, this also resulted in the spacing of the relatively expensive power-feed stations being limited by line power considerations, rather than by equalization and repeater load capacity considerations.

The selection of the type of equalizer terms, or "shapes," to be used and the number of terms in the equalizers, as well as the deployment of the shapes in the frequency domain, was based in part on computer simulations of the L5 channel as it was estimated to be, and in part on engineering judgments that evolved from experiences with earlier systems such as L3 and L4. For example, it was judged possible to meet the line repeater-cable loss matching requirement with about four or five peaks in the matching error as a function of frequency. (Five was the actual number.) It was further reasoned that (i) the action of the deviation equalizers, intended to complement the line repeater error function, would tend to double that number of peaks in the resultant "fixed equalized" characteristic; (ii) the midspan equalizer, while as simple as possible, should have a number of terms equivalent to the number of deviation peaks expected in the characteristic for which it was to compensate (8 to 10); (iii) the action of the midspan equalizer would tend to increase the number of deviation peaks in the resultant "coarse-equalized" characteristic by about the number of terms in the equalizer (presumably, 8 to 10). This leads to a main station equalizer being required to deal with a transmission characteristic

having potentially 16 to 20 peaks, whereupon the equalizer would correspondingly be required to have a similar number of terms. This type of reasoning provided starting conditions for various computer-aided optimization routines that ultimately resulted in the 10-term E1 equalizer and the 18-term E2 equalizer. Similar computer simulations were utilized to evaluate the effectiveness of such different types of equalizer shapes as the Bode-equalizer-derived "bump" shapes (as used in L4) and cosine equalizers (as used in L3). In each simulation undertaken, a given number of terms could be deployed more effectively with "bumps" than with alternatives, consequently leading to the selection of the "bump" equalizers for L5. While the initial analyses and selection of equalizer characteristics had to be based on *expected* L5 channel performance, the *final* deployment of "bump" shapes, as manufactured for the initial commercial application, was based on actual L5 repeatered line realizations in the L5 field trial. (The field trial took place between Cedarbrook and Netcong, N. J., from mid-1970 to mid-1972, with each of four coaxial lines equipped and evaluated over a distance of approximately 100 miles. The trial resulted in a variety of important system improvements.)

The manually adjustable equalizers are intended to be set upon initial installation and only rarely thereafter—for example, when a substantial increase in the amount of equipment operating in the manholes results in significant changes in the annual mean operating temperature of the repeaters. Readjustments of the E1 and E2 equalizers under such conditions will restore the mean-annual setting of the dynamic equalizers (E3) to midrange, will improve the overall transmission response (since the 28-term E1/E2 combination is more effective at equalizing the temperature offset effects than the four-term dynamic equalizer E3), and will improve signal-to-noise performance by reducing the maximum misalignment. Such readjustment would be accomplished out-of-service and would involve determination of the channel misalignment at a set of frequencies (three per adjustable term) selected to permit optimum channel equalization in a mean-squared-error sense. The misalignment of the channel is measured using programmable transmission measuring equipment under the control of what amounts to a special-purpose computer designated the Equalizer Adjustment Unit. The detailed implementation of equalizer adjustment is described in Ref. 1.

4.2.2.4 Other factors affecting system transmission. For completeness, two other factors that result in time-variant transmission effects are

mentioned here. One of these is the aging of the elements making up the system. Aging effects usually are much smaller and much slower than any effects already discussed. In a solid-state system designed with careful attention to component selection and component stresses, there is no aging mechanism comparable to that which was characteristic of the electron tube systems L1 and L3. In L5, aging effects are expected to be small enough to be insignificant with respect to transmission quality or with respect to such operational aspects as equalizer adjustment intervals.

The second of these effects is that associated with maintenance which, along with the aging effect, is normally one of the smallest time-dependent sources of change in the transmission response of a system. Over long periods of time there will inevitably be occasional repeater failures with subsequent replacement of these repeaters by spares not having the same transmission response as the failed repeater. (Present estimates of repeater reliability suggest a mean-time-to-failure in a maximum-length power span of 75 miles because of repeater failure at between one and two years. Individual failures are, of course, protected by the LPSS.) When they become large enough to be detected, both aging and maintenance effects would normally be compensated by one of the occasional readjustments of state equalizers E1 and E2.

4.3 Comparison of L5 features with some predecessors

When the characteristics of the L5 repeatered line are examined, it is evident that it shares many features with previous systems, and thus in some ways is a hybrid offspring of the L3 and L4 predecessors. For example, while the adjustable equalizers E1 and E2 consist of bump shapes like L4, the adjustments are made out-of-service and in such a way as to minimize the residual mean-squared error of the equalized channel, like L3. The cable-temperature effect is compensated by using both open- and closed-loop regulators which pre- and postequalize the changes in cable loss in equal parts, like L4. But the 22X deviation equalizer strategy of L5 is much more akin to the L3 approach. (In L4 there are five different designs, one of which is installed in every regulating repeater.) While all three systems utilize line-build-out netowrks to provide some spacing flexibility, they have fault-locating systems that are quite different. And only the L5 system supplements the basic fault-location system with a centralized, computer-operated transmission surveillance system

capable of measuring and monitoring a wide variety of system operating parameters.

V. CURRENT STATUS OF COAXIAL SYSTEM DEVELOPMENT

At the time of this writing, the development of the L5 system in its initial configuration had been completed with all important noise and transmission objectives having been met. Continuing efforts in the software offerings of the transmission surveillance system are expected to increase the already considerable capabilities for automatic and semiautomatic system maintainance, fault location, and trouble diagnosis. A modest level of continuing effort involving the optimization of deviation equalizer designs and modification of equalizer deployment should further improve the system transmission response and reduce system noise.

Effort is also under way to replace the existing mastergroup multiplex equipment (MMX-2c) with individual mastergroup translators, resulting in reduced noise contribution from that level of multiplex at lower cost. The possibility of alternative protection strategies for the jumbogroup level of multiplex are also being examined. In addition, the basic frequency allocation described in this paper is being reviewed with an eye toward possible spectrum reorganizations that would permit an increase in L5 capacity to 22 mastergroups using a new family of mastergroups and multimastergroup multiplex equipment.

Finally, questions continue to be raised with respect to future coaxial systems—whether or what or when they may be. Although advanced coaxial systems having substantially greater capacity than L5 seem clearly to be within the technological capabilities of the relatively near future, the need and economic desirability of such systems has not yet been established. Whether or not L5 becomes the last of the major long-haul coaxial developments will be determined in the years ahead primarily by considerations of circuit growth patterns and economic conditions and by the relative viability and availability of alternative instrumentalities such as possible new microwave radio, millimeter waveguide, and optical fiber systems.

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