The L-4 Coaxial System

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The L-4 Coaxial System is a new solid state broadband facility designed to transmit 3,600 long-haul message channels on standard 3/8-inch coaxial cable. This paper describes system design characteristics and operating features of the new system, discusses system power, protection switching, and fault location aspects, reviews the performance results from field trial and initial commercial service tests, and compares these results with predictions. This paper also summarizes the environmental factors and design concepts affecting the system's physical design.

I. INTRODUCTION

A new long-haul coaxial cable system, L-4, has been developed to transmit 3600 voice circuits on a pair of ⅜-inch diameter coaxial cables using frequency division multiplexing. A field trial was held in Ohio and completed successfully in early 1967. The system was turned up for commercial service in October 1967 on a route between Miami, Florida, and Washington, D. C.

The L-4 system is the latest in a family of long-haul coaxial systems. Each of the earlier systems was considered a large capacity system in its time.[1, 2] With the rising need for circuits and the advances in technology, each succeeding system has had increased capacity, as shown in Table I. Since system costs are dominated by the cost of the installed coaxial medium, the more efficient use of the line by the later systems effectively reduces the cost per circuit-mile. The increased capacity of the L-4 system, plus the relatively low cost of the solid state transmission equipment, has made it possible to reduce the cost of coaxial circuits by a factor of three compared with the cost of L-3 circuits.

In addition to its voice channel capacity, the principal features of the L-4 system are:

Table I—System Capacities

System designation	L-1	L-3	L-4
First commercial service	1941	1953	1967
Two-way voice channels per coaxial pair	600	1860	3600
Nominal repeater spacing (miles)	8	4	2
Typical route capacity per cable			
Number of coaxial units	8	20	20
Number of working pairs	3	9	9
Total two-way voice channels	1800	16,740	32,400

(*i*) All voice circuits satisfy the noise objective for 4,000 miles of transmission.

(*ii*) The system is completely solid state, thus minimizing maintenance and insuring maximum system reliability.

(*iii*) The nominal two-mile repeater spacing permits converting L-1 and L-3 systems to L-4 by adding repeater sites between those now used.

(*iv*) The L-4 frequency plan permits dropping any number of adjacent mastergroups without demodulating the other mastergroups.

(*v*) The number of continuous in-band pilots is minimized in anticipation of wideband analog and digital services.

(*vi*) All equalization adjustments are controlled from manned main stations, located as far as 300 miles apart, and can be made while the system is in service.

(*vii*) Fault location equipment is provided to locate a defective line repeater by measurements made from manned main stations.

II. FREQUENCY ALLOCATIONS

The line frequency spectrum for the L-4 system is shown in Fig. 1. The 600 voice channel mastergroup is a standard for long haul circuits in the Bell System. The six mastergroups are separated by 4 percent guard bands to facilitate dropping and blocking any number of adjacent mastergroups at a main station without demodulating the others. While this feature slightly increases the required bandwidth, it significantly improves the noise performance of the system by reducing the number of times that a through-mastergroup would otherwise be demodulated in a long circuit.

Even though it is not planned to transmit television on L-4, preliminary tests indicate that the same frequency allocation could be used for the television band as was used for L-3; the TV channel replaces mastergroups 2 and 3. This would permit the use of the television terminal developed for the L-3 system.[3] Specific operating problems will require further investigation if a need for television applications develops.

Two pilot frequency allocations are shown in Fig. 1. The only continuous in-band pilot is located at 11.648 MHz, in the guard band between mastergroups 4 and 5. This pilot is used in conjunction with regulating repeaters to eliminate, to a first order, the effect of cable temperature variations on the transmission characteristics of the system. A synchronizing pilot for the L-multiplex terminals is located at 512 kHz. This pilot, in conjunction with a band-edge regulator at main station repeaters, is also used to control the equalization of the low frequency end of the band.

A group of 12 command channels is located between 300 and 500 kHz. These channels are used for transmitting commands from manned main stations to the remote equalizers for system equalization. The band from 280 to 296 kHz is used for tones required by the protection switching system to coordinate line switches at both ends of a main station section. Finally, the frequency band from 18.50 to 18.56 MHz is used for 16 monitoring oscillator tones that are required for line repeater fault location.

III. SYSTEM DESCRIPTION—EQUALIZATION PLAN

3.1 *Basic Repeater*

Figure 2 is a block diagram of the L-4 system. The primary building block of the system is the basic repeater, nominally spaced at two miles. A fundamental principle used in designing the L-4 system was to keep the basic repeater as simple as possible. Consequently, this repeater has fixed gain, which is proportional to the square root of frequency, matching the loss at nominal temperature of 2 miles of ⅜-inch coaxial cable (see Fig. 3). The repeater consists of two fixed gain amplifiers and a power supply circuit. It has no gain adjustments but includes the option of a plug-in line buildout network which is selected when the repeater is installed. This network is used to compensate for differences in loss caused by repeater spacings less than two miles.

3.2 *Regulating Repeater*

The gain regulation necessary to compensate for changes in cable loss resulting from temperature variation is accomplished by inserting

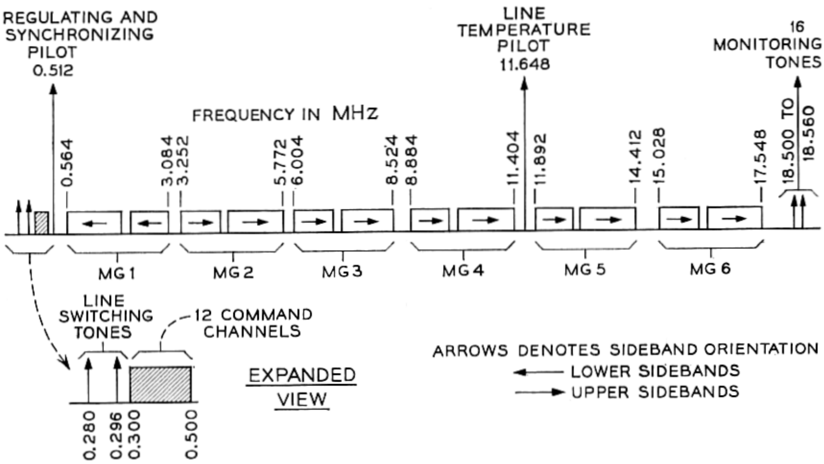

Fig. 1 — L-4 frequency allocations.

regulating repeaters in the L-4 line at maximum intervals of 12 miles. These repeaters include all of the components and features of basic repeaters and, in addition, include two dynamic gain adjusting circuits and a deviation equalizer.

One gain adjusting circuit, designated the postregulator, is controlled by the 11.648 MHz line pilot. This regulator varies the gain-frequency characteristic of the repeater to compensate for temperature associated changes in the loss characteristics of a regulating section—the cable and basic repeaters between two regulating repeaters. The second gain adjusting circuit, designated the preregulator, is controlled by a thermistor buried in the ground near the repeater in order to monitor ground temperature. This regulator preregulates by

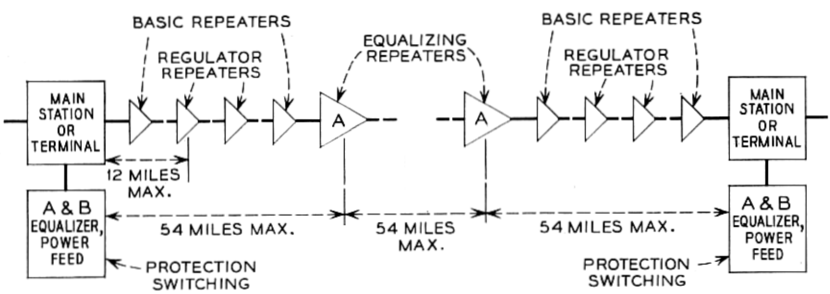

Fig. 2 — Typical L-4 repeatered line layout: maximum distance between main stations is 150 miles.

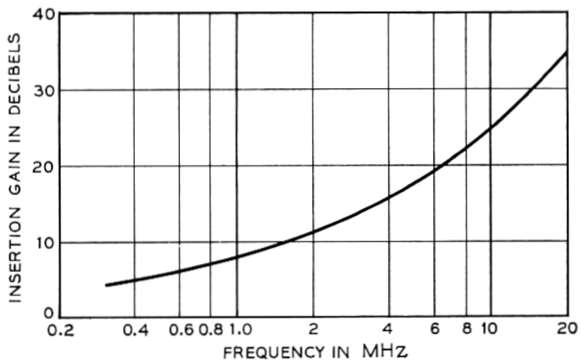

Fig. 3 — Repeater gain.

introducing approximately one-half of the gain-frequency correction required in a regulating section. The postregulator in the next regulating repeater introduces the other half of the necessary correction. By use of this technique of pre- and postregulation, it is possible to double the spacing between regulating repeaters without introducing excessive misalignment from cable temperature variations.

A deviation equalizer is included to compensate for transmission deviations caused by small but systematic deviations in the gain-frequency characteristics of basic and regulating repeaters from the loss characteristic of the coaxial cable. A family of deviation equalizers is required since the number of basic repeaters in a regulating section can vary between two and five. The deviation equalizer is a plug-in unit and is selected at the time the repeater is installed. Reference 4 gives a more complete description of the basic and regulating repeaters.

3.3 *Equalizing Repeater*

Equalizing repeaters, spaced up to 54 miles apart on the coaxial line, use all the components and features of regulating repeaters. In addition, these repeaters include six networks for adjusting the gain-frequency characteristic in order to compensate for random deviations introduced by the basic and regulating repeaters. The gain shape introduced by each network is effective over only a limited portion of the L-4 frequency spectrum. These networks, designated as an *A* equalizer, are adjusted remotely from manned main stations. These adjustments may be made while the system is carrying message service.

3.4 *Main Station Repeater*

Main station repeaters, spaced up to 150 miles apart, follow the building-block principles of the other repeaters. Each contains all the components and features of equalizing repeaters, ten adjustable equalizer networks, designated as a "B" equalizer, and a band edge dynamic gain adjustment. The sixteen adjustable *A* and *B* equalizer networks are remotely controlled from manned main stations. The band edge dynamic gain adjustment is controlled continuously by the 512 kHz out-of-band pilot. By means of the *A* and *B* equalizers and the band edge regulator in the main station repeaters and the *A* equalizers in the equalizing repeaters, it is possible to reduce the misalignment from all sources to about ±0.5 dB in a main station section. Reference 5 has a full description of the equalizing and main station repeaters.

3.5 *Repeatered Line Power Equipment*

In addition to the repeater, main stations also include equipment for powering line repeaters and for protection switching. The power equipment, consisting of dc-to-dc converters, provides a constant direct current of 520 milliamperes. This current is fed over the center conductor of the coaxial unit together with the carrier signal. Depending on the distance between main stations, the dc voltage between the center conductor and ground can vary between 360 and 1800 volts. The primary power source for this equipment is the −24 volt office battery in the main station. The use of dc power, rather than the 60 Hz ac power used by the L-3 system, makes possible a substantial reduction in the complexity of the line repeaters as well as considerably simplifying the engineering of the system. Reference 6 has a detailed description of the power equipment.

3.6 *Protection Switching*

Protection switching equipment permits substituting a spare coaxial line for one of the working lines in either direction of transmission. A protection switch is automatically initiated by either the 512 kHz or the 11.648 MHz pilots going out of limits. It is necessary to make the switch between lines as rapidly as possible in the case of a total failure to minimize the effect of the transmission interruption. In order to coordinate the operation of the protection switching equipment at the transmitting and receiving ends of a main station section, signaling tones are transmitted in the 280 to 296 kHz band. Use of the high transmission speed of the carrier frequencies on the coaxials for transmission of these signals results in maximum speed of operation of the switching equipment.

For maintenance purposes, manual operation of the switching equipment is provided. In effect, manual switches are made by simulating a failure of the 11.648 MHz pilot.

3.7 *Manned Main Stations*

The equalization plan requires that at least every other main station be manned. Furthermore, a main station is usually manned if circuits are added or dropped at that location (terminal main station). A manned main station contains, in addition to the equipment previously described, a remote control system and terminal equipment as necessary for adding and dropping mastergroups. The remote control system provides a means for telephone craftsmen to measure the gain-frequency characteristics of the line, to adjust equalizer network settings at equalizing and main station repeaters, and to monitor fault locating signals associated with repeater stations along the line. A control center handles only receiving lines but may be used with up to 100 such lines: as many as ten cables, each with as many as ten receiving coaxials units.

Gain measurements are made at selected frequencies by means of single-frequency signals transmitted to the control center from the input or output of any selected equalizing or main station repeater. The tones are turned on or off and equalizer adjustments are made in response to coded commands generated at the control center and transmitted over the frequency band 300 to 500 kHz. Logic and memory circuits at the equalizing and main station repeaters receive, interpret, and respond to the commands from the control center and maintain the desired settings of the equalizer networks.

Commands from the control center can also cause fault locating signals to be transmitted from monitoring oscillators associated with any group of 16 line repeaters to the control center over the band 18.50 to 18.56 MHz. An individual repeater is identified by the unique frequency assigned to it in the group of fault-locating signal tones. Repeater failure or other malfunctioning can be detected by monitoring equipment at the control center. Reference 7 has a more complete description of the remote control system.

3.8 *Terminal Main Stations*

As previously mentioned, mastergroup multiplex equipment is provided in terminal main stations where circuits are to be added or dropped. The transmitting circuits accept six 600-channel mastergroup inputs from standard L-multiplex equipment in the band between 0.564 and 3.084 MHz, the so-called universal mastergroup band.[8] By suitable steps of modulation, each of the six mastergroups is placed in the appropriate part of the L-4 frequency spectrum. The resulting high-frequency line signal lies between 0.564 and 17.548 MHz, as shown in Fig. 1.

Receiving mastergroup multiplex circuits separate the mastergroup signals from one another, demodulating each one to the 0.564 to 3.084 MHz band. They are then delivered to receiving L-multiplex equipment for further processing as required. The terminal equipment is described in Ref. 9.

IV. SIGNAL-TO-NOISE ANALYSIS

4.1 *Transmission Objectives*

The L-4 4,000-mile zero level message noise objective, 40 dBrnC0, is 4 dB more severe than the 44 dBrnC0 L-3 system objective. The 40 dBrnC0 is allocated as 39.4 dBrnC0 to the repeatered line and 31.2 dBrnC0 to the terminals.

Signal-to-noise analysis and field evaluation of the L-4 system indicate that the random noise, linearity and peak power of the line repeaters, together with several noise reducing techniques described in Section 4.2, permit the L-4 system to meet the 4,000-mile 40 dBrnC0 noise objective.

4.2 *Noise Reducing Techniques*

Several system features affecting all of the repeaters are incorporated in the L-4 system to minimize noise. Because line repeater gain makes first circuit noise and third order intermodulation considerably greater at higher frequencies, signal shaping in the form of pre-emphasis of the high frequencies is used to ensure a fairly constant signal-to-noise ratio, thus suppressing noise more effectively at high frequencies.

A second noise reducing technique is negative feedback. The repeater feedback characteristic is designed to be at its maximum (about 37 dB) at low frequencies. Owing to feedback stability considerations, this leads to about 15 dB of feedback at 17.5 MHz, the top of the message band. This feedback frequency characteristic helps to compensate for noise introduced by intermodulation distortion. It also interacts with the pre-emphasis characteristic to produce a very nearly constant signal-to-noise ratio throughout the transmission band.

A third noise reducing technique is the use of pre- and postequalization. On every line section—between basic repeaters, between regulating repeaters, between equalizing repeaters, and between main stations—equalization is about equally distributed between the two ends of the section. Pre- and postequalization reduces the maximum misalignment resulting from accumulated deviations, thus eliminating the need for large changes in equalization at one repeater. This in turn reduces the possibility of overloading individual repeaters and minimizes noise penalties resulting from unavoidable transmission gain-frequency deviations.

A fourth technique for reducing noise is frogging. Frogging is the frequency transposition of parts of the signal transmission band at points along the repeatered line. Mastergroup frogging produces two major transmission advantages: (*i*) a break-up of the tendency of limiting third order modulation products of the "$A+B-C$" type to add in phase and (*ii*) a reduction in signal-to-noise penalties which result from strongly systematic misalignment along the repeatered line. In order to satisfy signal-to-noise and equalization objectives, all mastergroups must be frogged at intervals not greater than 800 miles. No through mastergroup should occupy the same frequency assignment in the L-4 spectrum for more than one frogging section in a 4,000-mile circuit.

4.3 *Thermal and Intermodulation Noise*

Predicted busy hour zero level noise in all channels is nearly the same, at a value of 39.4 dBrnC0 for the repeatered line, as shown in Fig. 4. At the top and middle of the band, the dominant modulation source is third order and is in optimum relationship 3 dB below thermal noise. At the low end of the band, the dominant source is second order, which is in the desired relationship when equal to thermal noise. Such optimum relationships, and the essentially flat overall total noise characteristic, are achieved primarily by means of pre-emphasis of the transmitted signal, which involves the control of signal magnitudes to match precisely the frequency characteristic of the total noise shape at a convenient point of reference.

4.4 *Signal Level and Repeater Spacing*

The dominant level shaping factor in a system such as L-4 is the insertion gain of the basic repeater, which is a fixed gain device de-

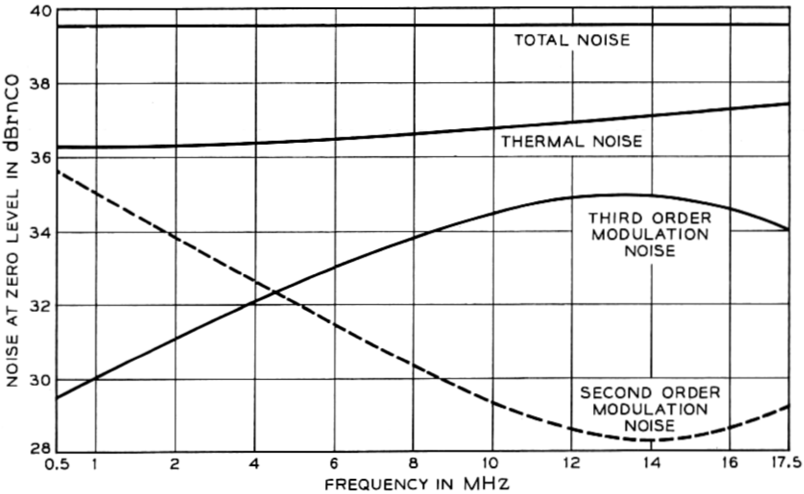

Fig. 4 — Zero level message channel noise for 4,000-mile L-4 high-frequency line.

signed to match the square root of frequency shape of the loss at nominal temperature of 2 miles of 3/8 inch coaxial cable. With reference to Fig. 3, gain varies from about 6 dB at the low end of the band to about 33 dB at the high end, resulting in a slope of 27 dB across the message spectrum. The second significant level shaping factor is the repeater noise figure-frequency characteristic; from the characteristic plotted in Ref. 4, the repeater noise figure ranges from 6 dB at the high end to 12 dB at the low end, which is in the direction of reducing the required signal shaping by 6 dB. Thus, the first approximation to the desired pre-emphasis is 21 dB. The final signal shaping is dependent on the details of the distribution and adjustment of modulation noise. A detailed signal-to-noise analysis indicates that 18 dB of pre-emphasis is optimum for the L-4 system. The amount of preemphasis is evident in Fig. 5, which shows the transmission level at the output of a line repeater.

Figure 6 shows a system block and level diagram, indicating design center transmission levels at points along the high frequency line.

4.5 *Misalignment—Margins*

In specifying transmission requirements for the line repeaters, margins are provided for signal to noise and overload penalties resulting from misalignment of signal levels as they are transmitted along the repeatered line. Provision is also incorporated for uncertainties which are present in the characterization of device and system parameters. Care is exercised in system design to minimize the required allowance for these effects in order to keep the requirements on the line repeaters as lenient as possible. Table II summarizes the allowances made for penalties and uncertainties in the L-4 system design. Measurements made in the Ohio field trial and on the Miami-Washington commercial system indicate that these allowances have been adequate.

V. ECHO CONSIDERATIONS

Analysis of the parameters that control echo performance indicates that for a 4,000-mile L-4 system, the long haul echo objectives will be met for the transmission of message, television, wideband data, and *Picturephone®* visual telephone service. These studies have assumed the use of the new and improved coaxial cable splice,[10] random cable reel length in accordance with repeatered line spacing rules, and a controlled sequence of cable manufacture and placement to optimize impedance match between coaxials at reel junctions. The analysis also takes account of the echo performance advantage, resulting from 800-mile mastergroup frogging, for message and data transmission.

The sum of echoes of all types in a 4,000-mile L-4 repeatered line is expected to be about 10 dB below the total allowable message system noise from all other sources. Repeatered line echo performance mar-

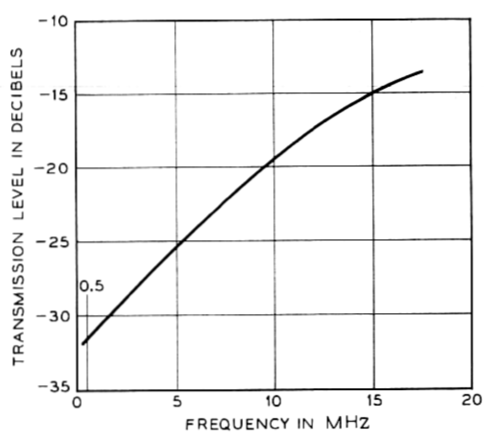

Fig. 5 — Transmission level at repeater output.

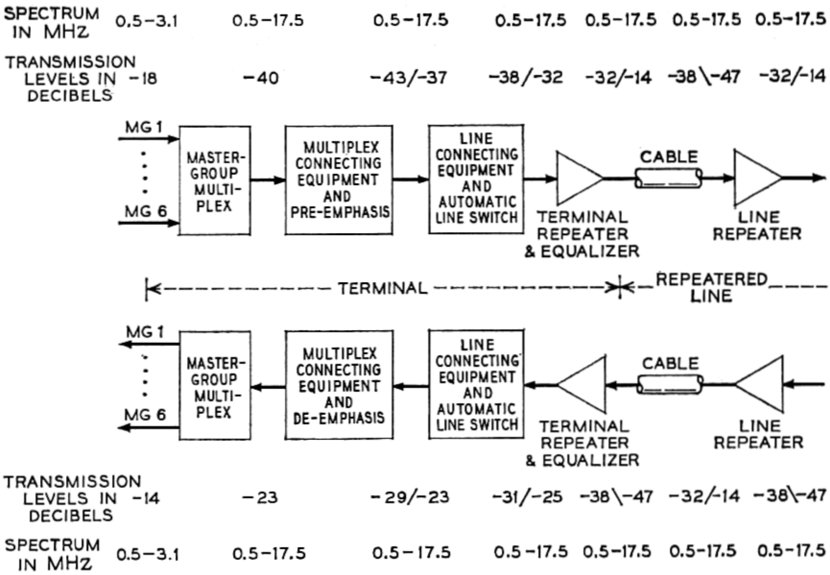

Fig. 6 — L-4 transmission levels.

gins of from 4 to 16 dB are predicted with respect to the appropriate 4,000-mile objectives for transmission of telephone, program, television, wide and narrow band data, and *Picturephone*® visual telephone service.

VI. FIELD RESULTS

This section summarizes the results of field transmission measurements made, initially on an L-4 field trial system in Ohio, and later on the first commercially installed L-4 system between Miami, Florida, and Washington, D. C. The overall results of these tests indicate that system noise, crosstalk, and transient characteristics are entirely satisfactory and in good agreement with theoretically predicted per-

TABLE II — ALLOWANCES FOR SIGNAL-TO-NOISE AND OVERLOAD PENALTIES BECAUSE OF MISALIGNMENT AND UNCERTAINTIES

Type of noise	Allowance (dB)
Thermal noise	2.5
Second order modulation	2.5
Third order modulation	5.0

formance. Line equalization capability meets the objective for a 150-mile main station link. Experience with the repeater monitoring oscillators shows that the method provides good capability for fault location and incipient trouble detection in the line repeaters.

6.1 *Signal-to-Noise Ratio Performance—Noise Loaded "V" Curves*

A noise-loaded "V-curve" performance extrapolated to 4,000 miles for a representative high end channel is shown in Fig. 7. Comparison of the measured and theoretical plots of Fig. 7 indicates that measured thermal and modulation noise components are in good agreement with theory, and that system transmission levels are at virtually optimum values for a fully loaded system.

6.2 *Impulse Noise*

Impulse noise performance margins are adequate under conditions dominated by extremely short duration impulses deriving from corona-like discharges in cable, connectors or repeater equipment, or dominated by impulse peaks generated by fully loaded systems. The corona-

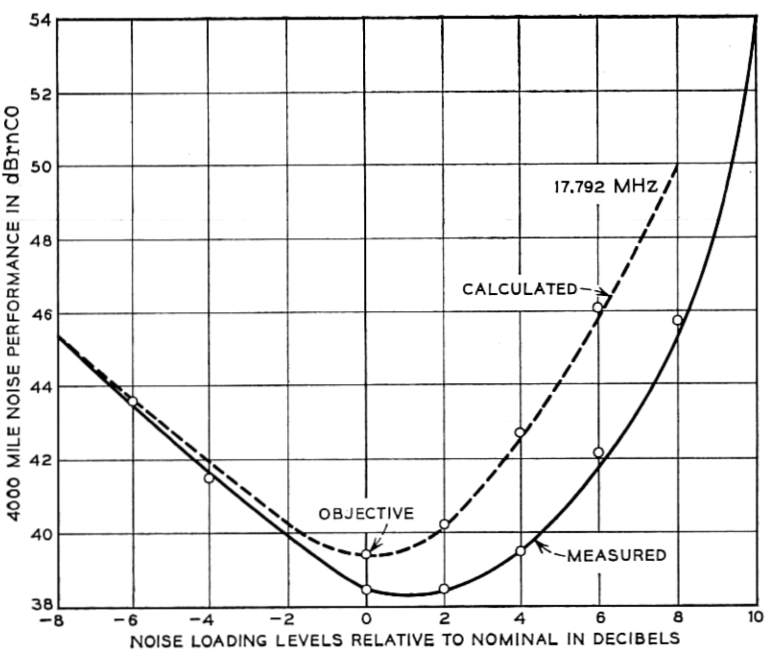

Fig. 7 — Noise performance extrapolated to 4,000 miles.

TABLE III —REPEATERED LINE LOAD CAPACITY

Required busy hour, fully misaligned rms load capacity = 10 dBm

Overlord criteria	Modulation	Differential gain	Impulse noise
Objective	$\Delta M_3 = 0.5$ dB	0.003 dB per repeater	1 count per minute 59 dBrnC0
Measured load capacity limit (dBm)	13	11	10
Load capacity margin (dB)	3	1	0

like impulses, sometimes referred to as "popping," are most severe when main station sections are operated at dc line voltages that approach the maximum of 1,800 volts. Under this operating condition, impulse noise performance is marginal when compared with the appropriate objective. However, only a relatively few such main station sections, approaching the maximum permissible spacing of 150 miles, would be encountered in a 4,000-mile system. Thus, a statistical advantage resulting from shorter average main station spacings and lower average operating line voltages, insures significant impulse noise margin in long haul circuits. Since the impulse noise magnitude in any given channel in the L-4 spectrum is sensitive to the line frequency of that channel, frogging rules which require transposition of mastergroups at maximum 800-mile spacings will help impulse noise margins by averaging the effects of impulse noise as a channel is frogged at specified intervals along the route.

6.3 *Repeater Load Capacity*

The line repeater load-carrying capacity has been evaluated with respect to three criteria: modulation, differential gain, and impulse noise. Measurements based on both the Ohio field trial and the first L-4 commercial installation indicate that the line repeaters provide sufficient peak power capacity to meet the requirements imposed by each of the three criteria with an overload margin which varies from 0 to 3 dB. Impulse noise performance appears to be most limiting, with essentially 0 dB of load carrying margin for a fully loaded, maximally misaligned 4,000-mile system. The load capacity margins observed for all three basic criteria are summarized in Table III.

6.4 *Crosstalk*

Repeatered line far end crosstalk shows a margin of approximately 3 dB versus the appropriate objective. This result reflects a substantial improvement over the results of the Ohio field trial, as a consequence of basic repeater design improvements instituted on the basis of field trial tests. Near end crosstalk performance is also satisfactory.

6.5 *Transient Response*

Transient response measured on 48 tandem regulating repeaters is well damped, with no observable tendency to spurious response or oscillation. Gain enhancement, with the pilot tone-modulated over a range of 0.01 to 1000 Hz, is within expected limits.

6.6 *Misalignment and Equalization*

Equalization of main station sections to within ±0.5 dB has been achieved, meeting the 150-mile objective. This result includes the effect of the band edge dynamic gain regulator previously discussed, which corrects for low-end misalignment variations caused principally by temperature sensitive elements in the line repeaters. Throughout the rest of the L-4 spectrum, there is adequate *A* and *B* equalizer range to correct for residual fixed misalignment from imperfect deviation equalization in the regulating repeaters.

VII. PHYSICAL DESIGN CONSIDERATIONS

This section discusses some of the broad considerations which went into the physical design of the L-4 system. Detailed descriptions of all the equipment is given in several companion papers.[4–7, 9, 10]

Full realization of the potential of the L-4 system depended upon the physical design of its many units. This was particularly true for the repeaters required to operate in a manhole environment not previously considered in the development of coaxial systems in the Bell System. Careful planning and design were also needed in the development of the connecting and terminating gear at underground, "hardened" main stations. Space in these buildings would always be at a premium; the heavy circuit concentrations of L-4 made efficient spatial design imperative.

7.1 *General Environment*

The environment new to the design of coaxial repeaters is their operation in manholes subject to flooding and possibly to the effects of nuclear attack. These two requirements had major impact on repeater design. Actually these problems had been faced before when the hardened, transcontinental L-3 system was planned. However, that was more than a decade after the system had been developed and placed in manufacture. Rather than redevelop the L-3 equipment to meet a new environment, underground buildings were designed to provide the needed environment for the repeaters. The buildings were made impervious to water, and shock mounts were provided for all equipment.

Manholes were chosen as the housings for all of the L-4 line repeater equipment because of the very substantial savings over the L-3 type of underground installation. Even a poured manhole is less expensive if complete waterproofing is not required. However, the newly developed prefabricated manhole that could be used at the smaller basic and regulating repeater sites had estimated costs far below any other construction method.

Two options were open in the design of repeaters to operate in such installations. Hermetically sealed repeaters could be developed. These always present manufacturing difficulties; even the best seals will at times be ineffective, in which case there usually is no warning of failure. The alternate method was chosen: mounting several unsealed units in gas-tight cases maintained at cable gas pressure. The gas pressure serves two purposes: it prevents moisture entrance through small defects which might develop in the seal, and it warns of major troubles through low pressure alarms.

Designing L-4 equipment to withstand the effects of nuclear attack posed many questions in the planning stages. Certain of the blast phenomena, high winds and thermal shock, would be of no consequence because of the system being underground. This, plus the concrete construction, would also nullify or greatly weaken some of the elements in nuclear fallout. Three areas of concern remained. Two could cause circuit outages or shorten component or device life: nuclear radiation and electromagnetic pulse. The other, ground shock, was a threat to the physical well-being of the equipment.

Since many new devices and components were to be used, their sensitivity to nuclear radiation could not be determined until long after design decisions had to be made. Because of this and the fact that the only real threat was via access or air openings, it was decided to rely on building design for protection. Consideration of the electromagnetic pulse problem led to the same conclusion. At the time of development planning, this phenomenon had not been completely characterized. Studies indicated that the usual precautions against lightning such as the lead cable sheath and shield wires over the cable, plus the metal apparatus cases, would suffice for the manholes. For the main stations, similar cable construction and overall building shields were considered adequate.

The approach to the third problem, ground shock, differed in the two environments, the manned main stations and the repeater manholes. For the manned main stations, consideration of all the types of equipment involved led to a generalized solution. Shock-mounted structures, where required by the over-pressures, would be used throughout and individual equipment would only need to meet nominal strength requirements.

Overall shock isolation did not seem economically feasible for the L-4 manholes. Therefore, the development of the manhole equipment was directed at making each repeater strong enough to withstand ground shocks other than those of direct hits.

Four other problems faced the physical designer. It was realized at an early development stage that the decision to power the line repeaters from points as far as 150 miles apart would result in severe insulation and safety requirements. To maintain the life integrity of the transistors, heat transfer mechanisms required the most careful study and implementation. A third and all-pervading consideration was reliability, not only of each device and component, but of every connection between them. Lastly, in every design decision, the operating frequencies had to be weighed; the upper limits were twice those of any previous carrier system.

7.2 *Hazardous Voltages*

Early in the preliminary development it was estimated that about one-half ampere of direct current at between 1,500 and 1,800 volts to ground would be needed to provide the power for the line repeaters. This combination posed two serious problems. Most important was a serious personnel hazard, especially in the line repeater installations. Here, under adverse conditions of crowded quarters and the possibility of standing water, even after pumping, each piece of equipment could be a lethal threat. Signs warning of hazardous voltages and care to be taken are helpful; but, in times of stress their message is often forgotten. It was therefore vital that in every step of physical design the possibility be absolutely minimized of anyone being able to contact a lethal voltage inadvertently. The high voltage was also a potential hazard to the equipment itself. It required most careful consideration of the circuit components and of the methods used to insulate the various parts of the equipment to withstand voltages much greater than the working values.

7.3 *Heat Considerations*

Heat generated in the amplifiers of a transmission system can have deleterious effects on the passive components. Most of all, the heat can severely shorten the life of the very devices which produce it. Every effort must be made to transfer the heat from the devices to the surrounding environment. For the electron tube L-3 system this meant devising means of reducing plate temperatures to tolerable levels. For the L-4 system it would mean extensive study and design innovations in order to achieve operating transistor junction temperatures that would permit the almost limitless life potential of these devices to be realized. Treatment of the heat problem would be different for main stations and for manhole repeater locations. In main stations, central office conditions apply. In manholes, however, radiation and convection effects are negligible. Solution of the problem would depend on the design of very efficient conductive paths from transistor junctions to the soil surrounding the manholes.

7.4 *Reliability*

Reliability for systems such as L-4 has particular significance. With repeaters spaced every two miles it has a vital relationship to reasonable maintenance costs. This will be even more important as our land systems of the future have even closer repeater spacings. In the planning stages of L-4 it did not appear that the ultimate reliabilities of submarine cable systems or satellites were justifiable. This was based on the practical maintainability of a land system when compared to an ocean or space system. In addition, the land system could be provided with switchable spare line sections economically to cover short-time outages. However, every effort would be made to provide the most reliable components and interconnections within economical design methods.

7.5 *Operating Frequency Considerations*

The last important physical design problem was that of the frequency range of L-4. Certain design considerations become obvious as the upper operating frequency is extended. Maintenance of coaxial integrity and more stringent shielding are immediately apparent. In addition the length of interconnections and the placement of units are vital. All of these factors and their relative importance had to be gauged in the physical design of the line repeaters and the main station equipment.

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