The *Picturephone*® System:

Baseband Video Transmission on Loops and Short-Haul Trunks

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Local Picturephone® *service will be provided using present telephone cable facilities. Three cable pairs are required for each* Picturephone *call, one for audio and two for video transmission. Underground cables will be used extensively and aerial facilities to a limited extent. A cable equalizer will provide shaped gain to compensate for cable loss from 5 Hz to 1 MHz. This article discusses the plan for providing baseband video transmission on paired cable facilities, the cable equalizer design features, the important rules for engineering the video transmission system, and the maintenance features.*

I. INTRODUCTION

For *Picturephone* service, baseband video signals are being transmitted on customer loops and short-haul interoffice trunks along routes similar to the ones used for present telephone service. It is economically attractive to use ordinary pairs of wires in the existing cables for video transmission. One pair is used for each direction of video transmission in addition to the pair used for the audio signal.

The basic element needed to provide video transmission is a cable equalizer, which provides shaped gain to compensate for cable loss. Present designs which are the subject of this paper are intended primarily for underground 22-, 24-, and 26-gauge paper pulp-insulated conductors. Underground cables are preferred since they are subject to less temperature variation and interference than aerial cables. Future systems now being designed will have temperature regulation and higher transmission levels, permitting the use of longer underground loops and trunks and the use of aerial facilities.

II. LOCAL VIDEO TRANSMISSION SYSTEM

The typical baseband video transmission system of Fig. 1 shows two *Picturephone* station sets interconnected by means of *Picturephone* loop and trunk facilities and two video switching offices. The audio portion of the *Picturephone* system is not shown nor discussed in this paper. Fixed shaped gain cable equalizers, designated with an "F" in Fig. 1, are used in the outgoing direction of transmission from switching offices to equalize for the carefully controlled office cabling and switching loss. Adjustable shaped gain cable equalizers, designated with an "arrow" in Fig. 1, compensate for a wide range of cable losses. The cable equalizer associated with the station set is mounted within the station set service unit as discussed in Ref. 1.

The video switching office transmission plan is shown in greater detail in Fig. 2. The video loop and trunk pairs are brought into the office through the main distributing frame (MDF) to the incoming and outgoing cable equalizers and then to the wideband distributing frame (WBDF) which is used for switch load balancing purposes. While loops connect to both the horizontal (H) and vertical (V) connections on the MDF in order to provide flexibility, trunks connect to

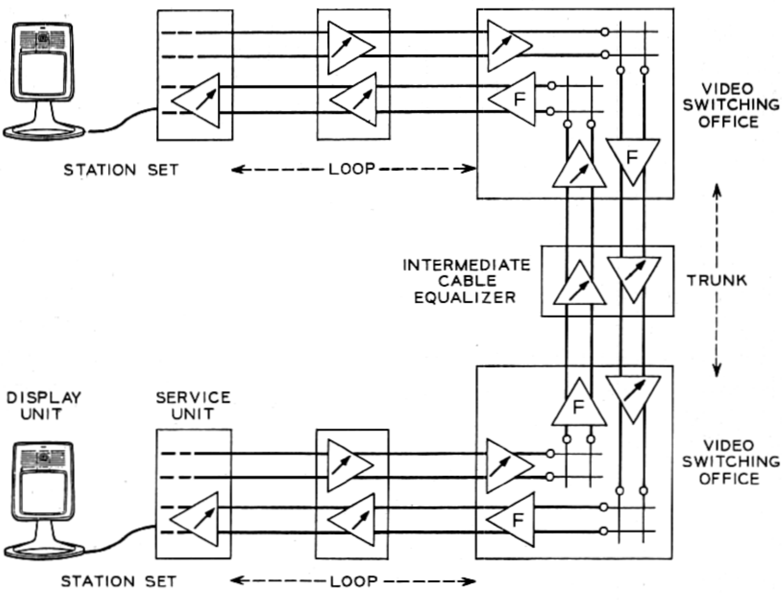

Fig. 1—Local video transmission system.

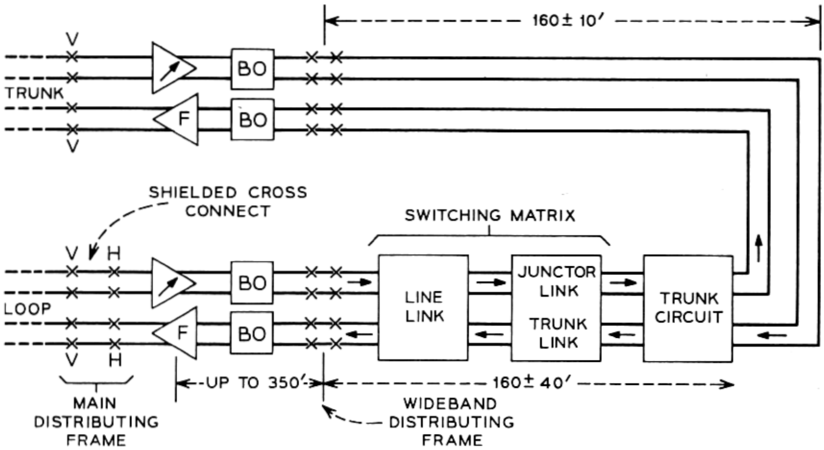

Fig. 2—Video switching office transmission plan.

only the verticals on the MDF since trunk rearrangements are not normally required. The cable length from the central office cable equalizers (COCE) to the WBDF is electrically built out to 350 ± 50 feet of 24-gauge cabling by means of the block labeled (BO). The loop transmission path from the WBDF through the three-stage video switching matrix to the trunk circuit is carefully controlled to 160 ± 40 feet. Likewise the trunk cabling from the WBDF to the trunk circuit is also carefully controlled to 160 ± 10 feet. Consequently, the transmission loss from the incoming loop cable equalizers through the central office to the outgoing loop or trunk cable equalizers is equivalent to the sum of (350 + 160 + 160 + 350) or 1020 feet of cabling. This central office transmission loss is compensated by the fixed shaped gain outgoing central office cable equalizer designated with an "F". The video switching office is discussed in more detail in Ref. 2.

Other situations, shown in Fig. 3, which require the use of cable equalizers include video transmission through customer located switching equipment, such as Wideband Remote Switches (WBRS),[2] Key Telephone Systems (KTS),[3] or Private Branch Exchanges (PBX)[4]. For video lines from zero to approximately 400 feet of 24-gauge cable between the station set and the KTS, passive station set build out networks (BO) are used instead of cable equalizers in order to build out these lines to a fixed amount of shaped loss. For the direction of transmission from the station set toward the KTS, this loss is post equalized by the KTS cable equalizer on the central office side of the

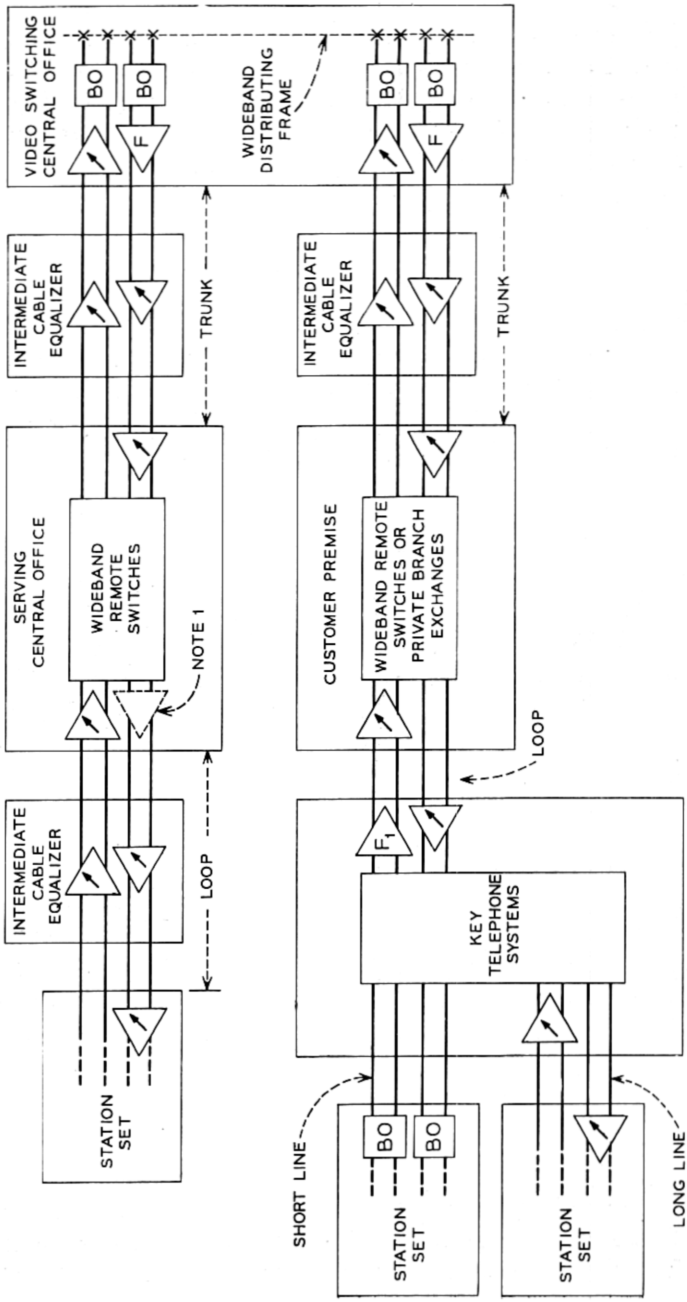

Fig. 3—Video transmission plan. (Note 1—used for supplying simplex power to ICE and for fault location.)

KTS designated F_1. The KTS cable equalizer on the central office side of the KTS designated with an arrow provides fixed pre-equalization for this built out KTS line loss for transmission from the KTS to the station set as well as adjustable equalization for the preceding loop cable section. For station sets beyond the range of the station set buildout networks, a station set cable equalizer and an additional KTS cable equalizer are required, as shown in Fig. 3.

A cable equalizer is required on all video loops and trunks coming into a PBX. Since PBX switching and transmission loss is negligible, no cable equalizers are required on outgoing loops and trunks.

A WBRS may also be used between the video switching office and the *Picturephone* station set. A WBRS is an extension of the video switching office and under its direct control but remotely located on the customer's premises or in another switching office not equipped for video switching. It is used to reduce video transmission costs by concentrating a number of loops into a lesser number of trunks connected to the controlling video switching office. The video transmission plan for a WBRS is essentially the same as for a PBX.

A customer's serving central office for telephone service may not be the same office used for switching his video calls, particularly in the early years of *Picturephone* service. These serving central offices may contain intermediate cable equalizers (ICE) or WBRSs which are used for the video portion of a *Picturephone* call. The facility which interconnects the serving central office with the video switching office is engineered to video trunk standards[5] in a manner similar to that used for baseband video trunks interconnecting two video switching offices. Such planning allows a graceful growth pattern; serving central office video equipment may progress from ICE to WBRS, and then ultimately the office may become a video switching office itself.

Loop transmission facilities are used to interconnect a PBX or WBRS on a customer's premises with a video switching office and are called trunks, although they are engineered[5] as a loop. All other transmission facilities not already specifically discussed (see Fig. 3) are engineered as loop facilities. Details of the engineering of the loop and trunk video transmission system are discussed in Section VI.

III. CABLE EQUALIZER DESIGN OBJECTIVES

The cable equalizer was designed to compensate primarily for the loss of 22-, 24- and 26-gauge pulp-insulated cable pairs, or mixtures thereof. The maximum cable equalizer gain was limited to 54 dB at

1 MHz. The criterion which was used to determine this maximum allowable equalizer gain was that the near-end crosstalk loss of the cable should be greater than cable equalizer gain by 14 dB for 99.9 percent of the installations. Consequently, the equalized cable section length is limited to approximately 6 kilofeet (kft) of 26-gauge cable and 8 kft of 22-gauge cable. This limit on cable section lengths is discussed more completely in Section 6.3.

The number of cable sections that may be cascaded to form one loop is, in practice, limited to from one to four sections due to the effects of changing cable insertion loss caused by changing ambient temperatures. In order to determine individual cable section design objectives such as tilt and random noise performance[5] from the loop objectives, it was assumed that a maximum of four cable sections comprise a loop. Powering capabilities and maintenance features were also planned on this basis.

The equalization objective was to compensate for the insertion loss of a cable section to within ±0.1 dB from essentially dc to 500 kHz, with the limits increasing to ±0.3 dB at 1 MHz. The amplitude response at the low frequency end of the band is determined by the loop tilt objective.[5] The tilt objective controls the amount by which a dc signal may change over a given interval of time when passed through an ac coupled facility. This requirement controls the allowed change in brightness of one horizontal scan line caused by the *Picturephone* transmission system itself. For a loop tilt objective of 1.5 percent per 100 μs and a four-section loop with five cable equalizers, each cable equalizer must satisfy a tilt requirement of 0.3 percent. We assume that only one RC low frequency coupling network is dominant. This assumption requires an RC time constant of at least 33 ms or a cable equalizer frequency response which is 3 dB down at 4.8 Hz.

The sinusoidal signal-handling objective for the cable equalizers was set at a nominal 0.75 V peak over the 1-MHz frequency band with a 6-dB margin against overload. The 6-dB margin allows for system misalignment and for changing cable insertion loss due to changing ambient temperature. The cable equalizer gain stability objective for a −40°F to +140°F temperature environment was set at ±0.2 dB at 1 kHz and ±0.3 dB at 1 MHz. The cable equalizers were also required to withstand lightning surges which are limited to 600 V by carbon block protectors.

The presence of large longitudinal signals on video pairs, principally 60-Hz signals, may overload the cable equalizer input network or reverse bias the Zener diode used to generate the cable equalizer powering voltage. The cable equalizer was required to tolerate a 10-mA peak longitudinal current and present a longitudinal impedance of 100 ohms at the input (equivalent to 1-V peak at the input) and 25 ohms at the output of a locally powered cable equalizer. The corresponding maximum open circuit longitudinal pair voltage that can be tolerated is approximately 2-V peak per mile for 26-gauge cable and 1-V peak per mile for 22-gauge cable. For the underground facilities that are comtemplated for the early years of *Picturephone* service, it is unlikely that longitudinal signals will exceed this level.

The weighted random noise objective[5] is −65 dBV* across a 100-ohm termination at the system zero *Picturephone* transmission level point (0 PTLP) for a loop. This noice objective includes cable equalizer noise and random interference from other systems coupled by means of cable crosstalk paths. The noise objective per loop due to only cable equalizers was set at −80 dBV, allowing a 15-dB margin for noise from other sources. Assuming four equalized cable sections per loop, the weighted noise objective per cable equalizer becomes −86 dBV. Combining the weighted noise characteristic[5] with the cable equalizer gain characteristic yields a frequency response with 13 dB of gain which is 3 dB down at 4.8 Hz and 500 kHz. The theoretical noise performance of an ideal noiseless cable equalizer with this indicated weighted frequency characteristic is −114 dBV. Hence, the cable equalizer noise figure objective is 28 dB.

The longitudinal balance (common mode rejection) of the cable equalizer input network† should be somewhat better than the longitudinal balance obtained from paired cable facilities so that cable facility performance is limiting. A longitudinal disturbance on one pair in a cable may be coupled to a *Picturephone* pair through the longitudinal-to-longitudinal near-end crosstalk path (with loss L_{LL}) and then converted to an unwanted transverse signal because of the finite balance of the input network. Even if the input network balance were infinite, an unwanted transverse signal is produced by coupling through the longitudinal-to-transverse near-end crosstalk path (with loss L_{LT}) of the cable itself. Consequently the input network balance (BAL_{in}) is given by equation (1); a 10-dB margin has been included to insure that cable balance is controlling at least 95 percent of the time.

$$\text{BAL}_{\text{in}} = L_{LT} - L_{LL} + 10 \text{ dB}. \quad (1)$$

* In this paper, dBV is defined as dB with respect to 1 V rms.
† Longitudinal Balance (dB) = Transverse Gain (dB) − Longitudinal Gain (dB).

Equation (1) was used to determine the input network balance objective from 30 kHz to 1 MHz and is shown as part of Fig. 4.

For the frequency range from 600 Hz to 30 kHz, the single frequency interference (SFI) requirement[5] of −65 dBV at system 0 PTLP was used to determine the input network balance objective. If the maximum longitudinal signal (LS) present at the input of the cable equalizer is −10 dBV* and the maximum cable equalizer gain G is 10 dB for the 600 kHz to 30 kHz frequency range, then the input network balanced should be 65 dB as given by equation (2).

$$BAL_{in} = LS - SFI + G \tag{2}$$

For the low frequency range from 60 Hz to 600 Hz, the input network balance should be such that a 60-Hz longitudinal signal at −3 dBV, the maximum tolerable longitudinal signal, should result in a transverse signal no greater than the −38 dBV power hum requirement[5] for a loop facility. Assuming a cable equalizer low frequency gain of 10 dB, the input network balance at 60 Hz should be 45 dB. The composite balance objective for the input network is shown in Fig. 4.

The balance objective for the balanced output network of the cable equalizer is important to prevent coupling of a video signal from one video pair to another or to another type of transmission system. Any unbalance of the output network allows transverse signals to be converted to longitudinal signals and then coupled to other pairs via the longitudinal-to-transverse near-end crosstalk path with loss L_{LT}. Even if the output network balance were infinite, a transverse signal on one pair would cause a transverse signal on another pair via the transverse-to-transverse near-end crosstalk path with loss L_{TT}. Consequently the balance of the output network should be greater than $L_{TT} - L_{LT}$ plus a 10-dB margin, resulting in a 20-dB balance objective for the output network for most of the frequency band of interest.

Output network balance objectives more stringent than the 20-dB balance discussed above are required for remotely powered intermediate cable equalizers which are floating with respect to earth ground. The feedback path around a floating cable equalizer, shown in Fig. 5, is one of two possible feedback paths which involves the

* Most of the longitudinal signal tolerance of the cable equalizer should be reserved for 60-Hz type pickup, and harmonics thereof. Hence it is reasonable to require that all other types of longitudinal interference on cable pairs are at least 7 dB down from the 1 V peak longitudinal signal tolerance level, or −10 dBV or less.

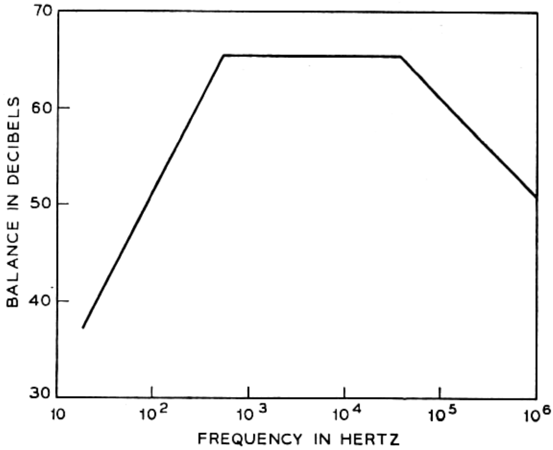

Fig. 4—Input network balance objective.

balance of input and output networks and the longitudinal cable impedance which is referenced to earth ground. Analysis of these two feedback paths yields essentially the same balance requirements for the output networks; hence, only the situation shown in Fig. 5 will be discussed here.

Because of the finite balance of the output network, a transverse signal at the cable equalizer output is converted to a longitudinal signal with loss BAL_{out} and is coupled to the input of the cable equalizer through the longitudinal cable impedance at the input and output of the cable equalizers. This longitudinal signal is then converted to a transverse signal by the unbalance of the input network with an additional loss BAL_{in} and then amplified by up to 54 dB, the maximum cable equalizer gain at 1 MHz. Consequently, $BAL_{out} + BAL_{in}$ should be significantly greater than 54 dB at 1 MHz. If the input network balance is 50 dB at 1 MHz, then the output network balance should be much greater than 54 − 50 or 4 dB. The output network balance requirement was chosen as 40 dB over the 1-MHz band of interest primarily because this amount of balance is readily achievable, as indicated in the next section, and provides ample attenuation to suppress the unwanted feedback.

IV. CABLE EQUALIZER DESIGN

The cable equalizer consists basically of an input network, a static equalizer, and an output network as shown in Fig. 6.

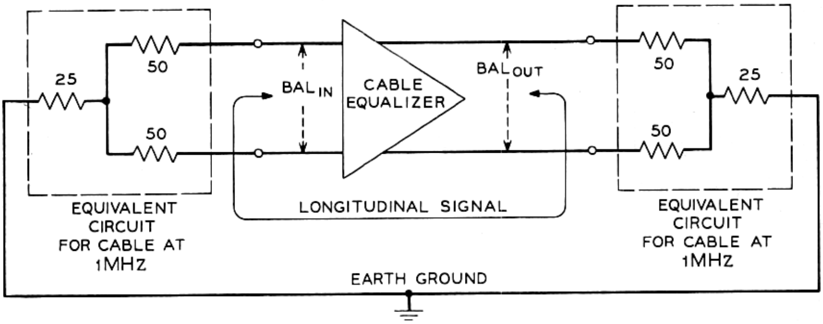

Fig. 5—Feedback path around a simplex powered cable equalizer with finite input and output balance.

The input network is a high impedance differential amplifier which converts the incoming balanced signal to the unbalanced mode for equalization. This network is capacitively coupled to the cable and provides a fixed center tapped 100-ohm resistive termination to the cable. This 100-ohm termination was chosen because the characteristic impedance of pulp cable pairs is approximately 100 ohms above 100 kHz. It is this coupling network which primarily determines the 4.8-Hz 3-dB corner frequency of the cable equalizer. A flat gain

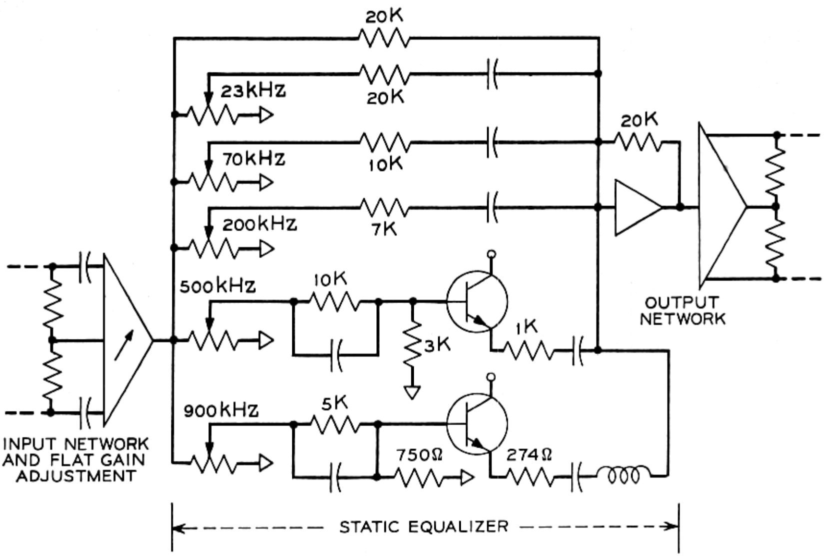

Fig. 6—Cable equalizer.

adjustment is provided with a −6 dB to +10 dB gain range. The worst-case longitudinal balance (common mode rejection) of the input network essentially meets the balance objectives as outlined in the previous section and shown in Fig. 7.

The output network is a dc coupled, unity gain, differential power amplifier which converts the unbalanced static equalizer output signal to the balanced mode for transmission on the cable. It provides a fixed center tapped 100-ohm resistive termination to the cable. It requires 60 mA of dc bias current to produce a signal handling capability of 1.5 volts peak above average into a 100-ohm load. The typical longitudinal balance of the output network exceeds the 40-dB balance requirement from dc to 1 MHz as shown in Fig. 8.

The static equalizer is basically a shaped gain amplifier that compensates for the high frequency loss in the transmission line. The desired gain shape is achieved by combining the currents from six parallel paths by means of an operational amplifier. The magnitude of the current through five of the paths is controlled by five potentiometers, giving a high degree of flexibility in compensating for a wide variety of cable loss shapes. Each potentiometer is identified with its respective adjustment frequency, and each potentiometer drives a network whose critical frequencies occur in the vicinity of its adjustment frequency. These critical frequencies were chosen as 23 kHz, 70 kHz, 200 kHz, 500 kHz, and 900 kHz. The critical frequencies increase and the impedance levels decrease for successive paths,

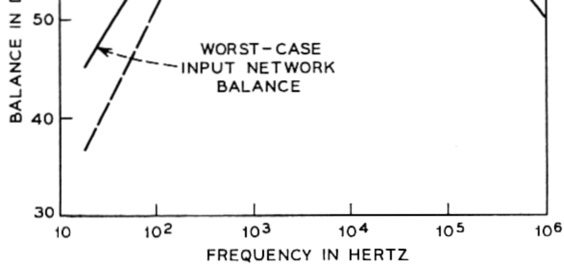

Fig. 7—Worst-case input network balance characteristic.

thereby providing greater gain at higher frequencies. Greater gain slopes are achieved at the higher frequencies by providing a cascade of RC networks.

In designing the six parallel paths that form the heart of the static equalizer, it is important to guarantee that this overall adjustable network is a minimum-phase network for any expected potentiometer setting in order to provide the proper phase equalization. A sufficient condition is that no two parallel paths shall have a phase difference of 180° or greater in their output currents at any frequency. This sufficient condition is easily satisfied by the adjustable network.

The adjustable static equalizer has a gain range of from 0 to 23 dB at 1 MHz. Not shown in Fig. 6 are two additional cascaded stages of fixed shaped gain with critical frequencies in the 200-kHz to 1-MHz frequency range which may be added by screw switches, one for medium length loops and both for long loops. They provide additional gain of 7 dB and 14 dB at 1 MHz respectively, and lesser amounts at lower frequencies. The use of these screw options reduces the range of shaped gain required for the adjustable static equalizer and helps in obtaining the steep (on the order of 18 dB/octave) gain versus frequency slope required for long cable sections at high frequencies. It would be difficult to achieve an 18 dB/octave slope entirely from

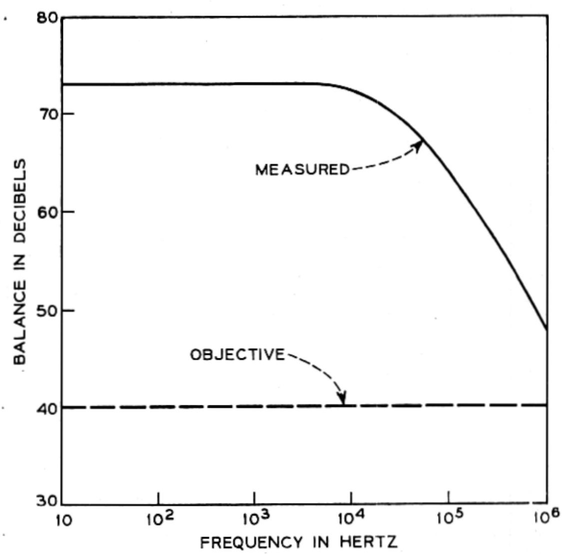

Fig. 8—Typical measured output network balance characteristic.

the adjustable network and still meet the sufficient condition for minimum phase.

The pole and zero locations for the individual parallel paths within the adjustable static equalizer and the two fixed shaped gain networks were first determined roughly by laboratory experimentation so that the equalizer would perform properly for any cable length up to the maximum length for both 22- and 26-gauge pulp cable. The performance criteria were gain range at the five test frequencies and closeness of fit between test frequencies. After the static equalizer configuration was determined experimentally, the optimum adjustment frequencies and network values were determined by computer simulation. By this process it was found that five potentiometers were required within the adjustable static equalizer in order to achieve the equalization design objective for a section of cable of ± 0.1 dB up to 500 kHz and increasing to ± 0.3 dB at 1 MHz.

Thus, by means of five potentiometers and two screw options within the static equalizer and the 10 dB of adjustable flat gain associated with the input network, gains from 0 to 10 dB at low frequencies and 0 dB to 54 dB at 1 MHz are achieved, sufficient to equalize up to about 6 kft of 26-gauge pulp cable and 8 kft of 22-gauge cable.

Also included in the static equalizer is a 3-pole low-pass Butterworth filter which attenuates out-of-band frequencies but has a negligible effect on the amplitude response up to 1 MHz. This filter helps prevent system oscillations in the vicinity of 1.3 to 2.0 MHz due to cable near-end crosstalk, as discussed in Section 6.3.

Alignment is accomplished by transmitting six frequencies, one at a time, over the section of cable to be equalized. A low frequency tone at 1 kHz is used to adjust the flat gain of the input network and five tones (from 23 kHz to 900 kHz) are used to adjust the five potentiometers within the static equalizer to obtain an equalized cable section frequency response flat to 1 MHz and approximately 3 dB down at 4.8 Hz and 1.3 MHz. The five static equalizer adjustments are not completely independent, however, and it is necessary to cycle through the alignment frequencies about six times to obtain an alignment accuracy of better than 0.05 dB at the alignment frequencies. This accuracy of 0.05 dB is readily achievable and was chosen so that the misalignment caused by potentiometer maladjustment is small compared to the total facility misalignment error caused by such things as cable equalizer gain drift due to ambient temperature changes, the absolute accuracy of the test instruments used during alignment, and the effects of temperature changes on cable insertion loss.

The amplitude and phase response of an equalized 6-kft section of 26-gauge pulp cable is shown in Fig. 9. The asterisks in Fig. 9 indicate the alignment frequencies. The error in the amplitude response is less than 0.1 dB up to 600 kHz and less than 0.2 dB up to 1 MHz. The phase distortion of Fig. 9 is due principally to the sharp cutoff above 1 MHz of an equalized cable section. The time delay distortion is about 75 ns at 600 kHz and 150 ns at 800 kHz. As an example of the significance of this amount of time delay distortion, a cascade of two to three such sections of cable, i.e., 15 kft of 26-gauge, uses the entire loop echo rating allocation as discussed in Section 6.2 and Ref. 5. A later version of the cable equalizer will have less time-delay distortion.

Other characteristics of the cable equalizer include a measured weighted noise of −90 dBV corresponding to a noise figure of 24 dB which exceeds the objective discussed in Section III by 4 dB. The overload performance of a typical cable equalizer is plotted in Fig. 10 for peak sinusoidal signal amplitude versus the signal-to-harmonic distortion ratio (S/H.D.). For a 0.75-V peak sinusoid which is the nominal transmission level for the cable equalizer and is 6 dB below the clipping level, the S/H.D. is 55 dB.

The cable equalizer was designed for a −40°F to +140°F temperature environment. Since the cable equalizer does not contain temperature regulation, the temperature environment for cable itself is restricted to the considerably narrower limits for underground or

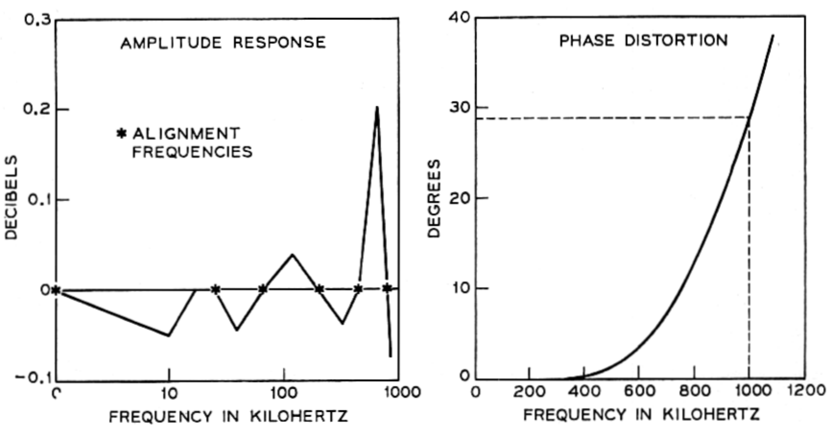

Fig. 9—Typical measured frequency response-equalized 6-kft 26-gauge pulp cable.

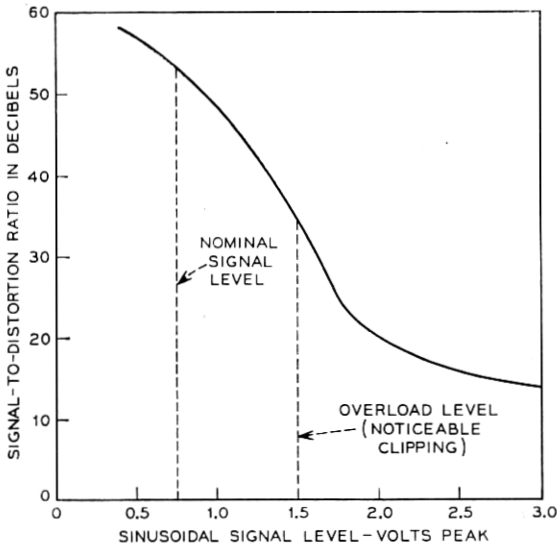

Fig. 10—Typical measured cable equalizer overload performance.

buried cables of about 30°F to 80°F. The effect of changing temperature on the gain of a typical cable equalizer at 1 kHz and 900 kHz is shown in Fig. 11. The effect of temperature change at other frequencies between 1 kHz and 900 kHz tends to lie within these two curves. Gain changes are less than the objective of 0.2 dB at 1 kHz and 0.3 at 900 kHz over this temperature range. For a restricted temperature range of 30°F to 120°F, gain changes are within 0.1 dB at all frequencies.

Preliminary studies of reliability indicate a mean-time-to-failure of 40 years for a one-way cable equalizer. For a loop shown in Fig. 1 which includes a two-way central office cable equalizer, a two-way intermediate cable equalizer, a one-way station set cable equalizer, and associated power supplies, the mean-time-to-loop-failure is approximately seven years.

A one-way cable equalizer which mounts in a PBX, a WBRS, a central office, and in a manhole consists of two printed wiring cards 6″ wide by 7″ long that are sandwiched together so that all components are toward the interior of the sandwich and the printed wiring is exterior as shown in Fig. 12. The resulting packages mount on $1\frac{1}{8}$″ centers. Each one-way cable equalizer consists of 40 transistors, 13 diodes, 40 varistors used primarily for lightning protection, 120 resistors, 40 capacitors, two inductors, and six potentiometers. Cable equalizers for Key Systems are similar electrically and physically (7.5″ wide, 5″ long, and 1.5″ thick). For station sets, the cable equalizer is also similar electrically, but all components are mounted on one printed wiring card 5.5″ wide and 10.5″ long. A typical central office bay with cable equalizers is shown in Fig. 13.

V. POWERING AND LIGHTNING PROTECTION

Each one-way cable equalizer requires approximately $\frac{1}{8}$ ampere at −24 volts or approximately 3 watts. It may be locally powered or, for the case of ICEs, it may also be simplex powered from the central office or a customer located WBRS. ICEs in manhole apparatus cases may be simplex powered only; ICEs between a PBX and a KTS or station set may be locally powered only. A simplex powered loop is shown in Fig. 14.

A +130-volt battery potential is applied through a current regulator (CR) to the center tap of the incoming central office loop or trunk cable equalizer input network and then to the cable pair (this cable equalizer is powered from the local regulated −24 V supply). Powering current travels over the transmission pair in the direction opposite that of video transmission. At the next equalizer location, the powering current is routed through the center tap of the output network, used to power that cable equalizer, and then applied to the next cable section through the center tap of the input network.

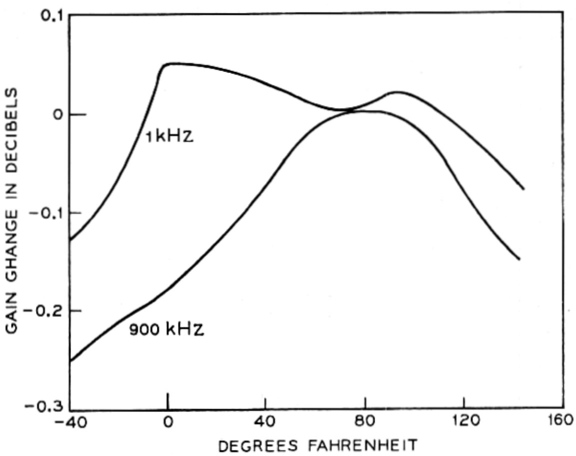

Fig. 11—Typical measured cable equalizer gain variation with temperature.

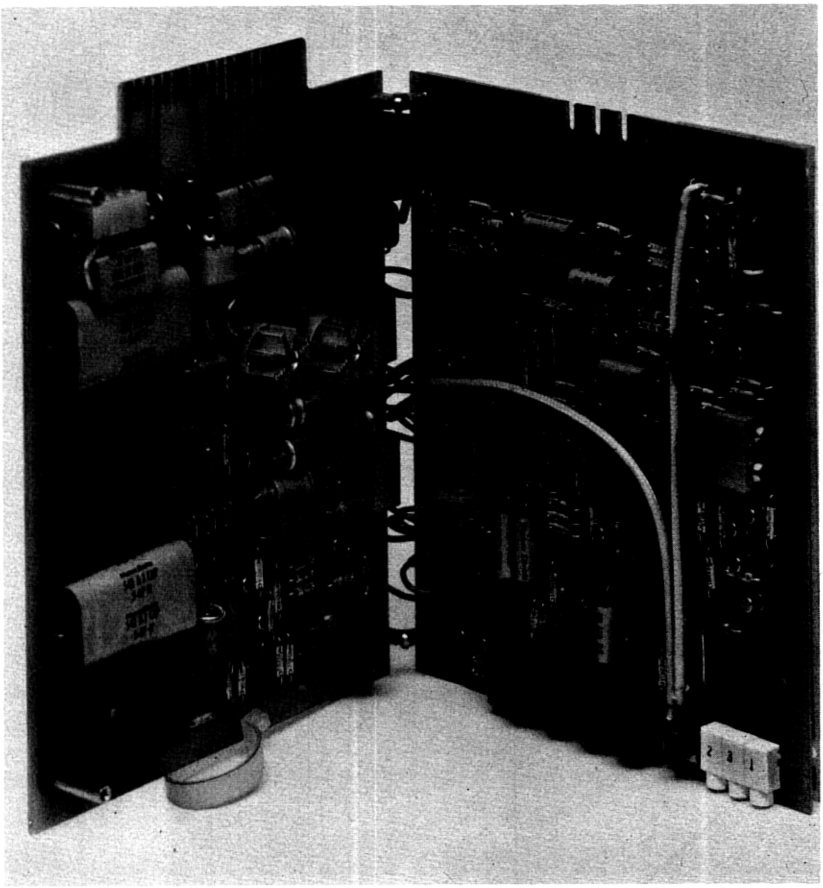

Fig. 12—Cable equalizer—open view.

At the last intermediate cable equalizer, the powering current is looped back from one video pair to the other, used to power the remaining loop cable equalizers, returned to the central office where it powers the outgoing central office equalizer, and then returned to ground, −48 V, or −130 V, depending on the number of ICEs and the length and gauge of the loop facility. Up to three intermediate cable equalizers may be powered in series.

Table I tabulates the simplex powering limitations in terms of cable gauge and length from the central office to the last intermediate cable equalizer. The total loop length consists of the simplex powered section plus the last section which is not simplex powered. The final loop configuration must simultaneously satisfy three separate conditions: simplex powering limitations shown in Table I, cable equalizer spacing as dictated by engineering considerations discussed in Section 6.3, and maximum loop or trunk length limitations as dictated by the allowed transmission impairments as discussed in Section 6.2.

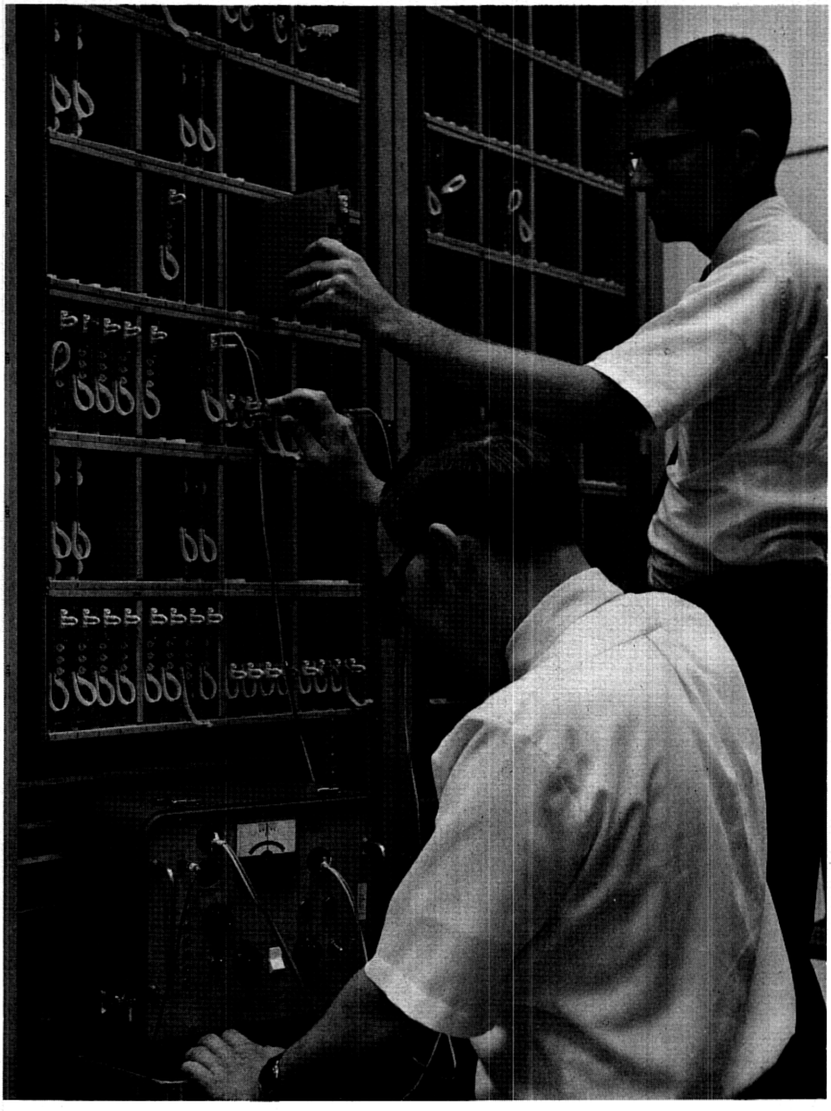

Fig. 13—Central office cable equalizer bay.

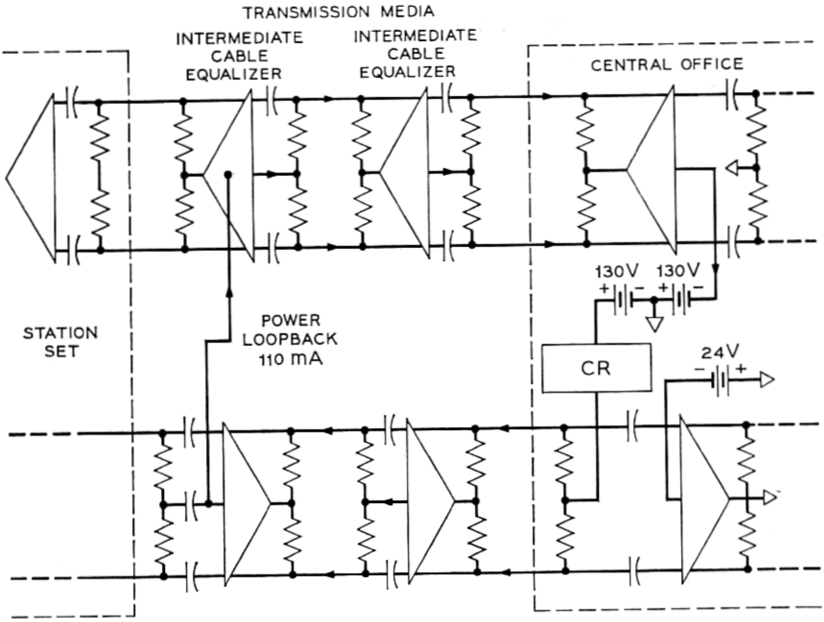

Fig. 14—Simplex powering.

Cable equalizer powering and lightning protection features are shown in Fig. 15 for a simplex powered cable equalizer. A similar arrangement is used for local powering from −24 V. A Zener diode connected between the center tapped 100-ohm input and output terminating resistors is used to generate the 14.5 V required to power the cable equalizer circuitry. A total of 20 varistor diodes at the input and 20 at the output are used to provide low voltage lightning protection at the cable equalizer input and output. Twenty diodes are required in order to prevent unwanted conduction by dc bias voltages and ac video signals. Standard carbon blocks or gas tubes are used for high voltage lightning protection.

VI. ENGINEERING THE TRANSMISSION SYSTEM

Picturephone service will be provided using present telephone cable facilities for transmitting baseband video signals on customer loops and short-haul interoffice trunks. These facilities have been installed over the years primarily for an economical and flexible voice-frequency communications network. Planning, engineering, installation, and administrative considerations different from those for voice grade service are required for *Picturephone* service because of the more stringent transmission requirements.

6.1 *General Cable Facility Considerations*

The cables recommended for baseband video transmission are buried or underground 22-, 24-, and 26-gauge pulp-insulated 0.083 μF/mile cable, which are subject to less temperature variation and radio frequency interference than aerial cables. While not a preferred type, 19-gauge pulp-insulated 0.083 μF/mile cable may also be used. Cables of the unit type construction are preferred because of superior crosstalk properties. Cable sections placed prior to 1940 are to be avoided, if possible, since higher attenuation and impedance irregularities may result from paraffin filled splices, plugging compound, and lower insulation resistance at splice joints. If necessary 19-, 22-, 24-, and 26-gauge 0.083 μF/mile plastic insulated cables (PIC) may also be used.

In those few cases requiring cable facilities so long that they cannot be served on the above indicated cable pairs, 16-gauge cable used for commercial TV transmission may also be used to provide *Picturephone* service.

Mixtures of the above cable gauges with the same capacitance characteristic are permitted in a video telephone facility. Cable equalizers are not required for isolation purposes at the gauge change interface.

All load coils and build-out capacitors must be removed from cable pairs used for video telephone service. Any bridge tap in excess of 100 feet must be removed; in addition, the sum of all bridged taps on a loop or analog trunk should not exceed 200 feet.

Tests at Bell Laboratories have indicated that video cable pairs without at least 15 mA of dc current flowing must have soldered or

TABLE I—SIMPLEX-POWERING LIMITATION

Gauge	Maximum Distance in kft to Last Simplex Powered ICE		
	One ICE (+130V / GND)	Two ICES (±130V)	Three ICES (±130V)
26	6	11	9
24	10	18	14
22	16	29	23
19	32	58	46
16	64	117	92

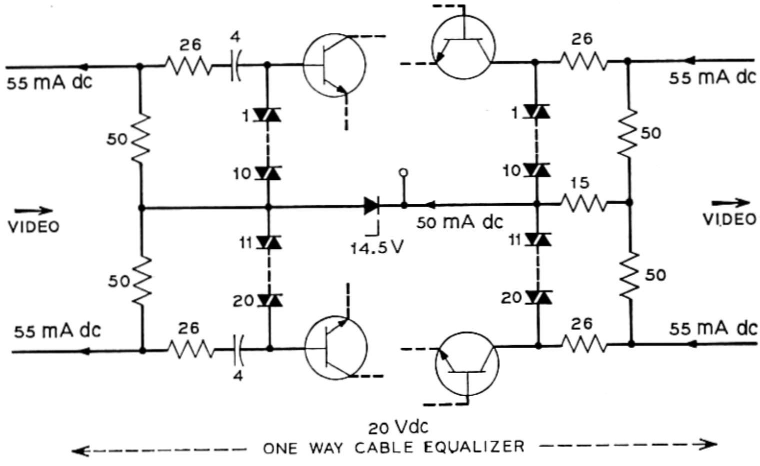

Fig. 15—Powering and lightning protection.

crimped splices in order to guarantee low-resistance joints. Hand twisted splices tend to form high-resistance joints in time without dc current or without high ac potentials such as 20-Hz ringing signals. For video telephone pairs, soldered joints or crimped splices are required in most instances, i.e., for those facilities without simplex-powered intermediate cable equalizers (ICEs) and the last section of those simplex-powered ICEs.

Wideband data systems and carrier systems such as T1, T2, and N cannot be transmitted in the same unit, complement, or splicing group with video telephone pairs. When unit integrity is maintained, *Picturephone* pairs may be in units adjacent to such facilities only if the direction of transmission is the same. Regardless of the direction of transmission, *Picturephone* pairs may be in units nonadjacent to such facilities. Where unit integrity is not maintained, separate sheaths are required to separate *Picturephone* circuits from the above systems.

Thermal noise and impulse noise are expected to be within the acceptable levels as outlined in Ref. 5. Radio frequency interference (RFI) from commercial radio broadcast stations is also expected to be within acceptable levels for single frequency interference[5] on underground or buried facilities providing that all branch pairs entering a sheath containing *Picturephone* circuits are likewise underground or buried. Aerial pairs for video circuits are permitted for distances up to 500 feet only if there is a continuous, unbroken sheath on the aerial portion and if the aerial portion is approximately one mile or more from a radio station broadcasting antenna. In addition, branch pairs entering a sheath containing video telephone circuits must satisfy the aerial cable rule to a distance of 6 kft from the branch point. These aerial cable restrictions will be relaxed for future systems having higher transmission levels.

Unbalanced private line circuits widely used for dc telegraph, burglar alarms, and clock synchronization may act like antennas and bring RFI into cables with video telephone circuits. Consequently these unbalanced circuits should not be in the same unit with *Picturephone* circuits, assuming unit integrity. If unit integrity is not maintained, the unbalanced circuits should not be in the same sheath with *Picturephone* circuits.

Also because of RFI, no more than 200 feet of unshielded inside wiring, not contained in metal pipe or building raceway, may be used in a reinforced concrete or structural steel building which itself provides shielding. In buildings not providing shielding, such as wooden structures, all inside wiring cable should be shielded.

6.2 *Loop and Trunk Lengths*

Baseband video loop and trunk lengths are presently limited by two dominant factors, phase distortion discussed previously and the effects of temperature on cable insertion loss as shown in Fig. 16 for typical 22- and 26-gauge pulp cable pairs. To evaluate the effect of these transmission impairments, a technique known as "echo rating"[6] is employed.

The echo rating for the effects of temperature change on cable insertion loss can be expressed by equation (3), where echo rating (ER) is in dB, the magnitude of temperature change (T) in degrees Fahrenheit, cable length (L) in kilofeet*, and the subscript on (L) representing cable gauge.

$$ER_T = -79 + 20 \log_{10} \cdot \left[T \cdot L_{26} + T \cdot \frac{L_{24}}{1.4} + T \cdot \frac{L_{22}}{4} + T \cdot \frac{L_{19}}{6} + T \cdot \frac{L_{16}}{8} \right] . \qquad (3)$$

Similarly, equation (4) shows the echo rating result due to phase distortion as a function of cable gauge and length.

$$ER_\Phi = -45 + 20 \log_{10} (1/6) \left[L_{26} + \frac{L_{24}}{1.2} + \frac{L_{22}}{1.5} + \frac{L_{19}}{2.25} + \frac{L_{16}}{5} \right] . \qquad (4)$$

* Equations (3) and (4) are for pulp insulated pairs for 19- through 26-gauge cables and plastic insulation for 16-gauge cables.

The combined effect of these two impairments is such that the individually computed echo ratings add together on a power basis as shown by equation (5).

$$\mathrm{ER_{TOTAL}} = \mathrm{ER}_\Phi + 10 \log_{10}\left[1 + \log_{10}^{-1}\left(\frac{\mathrm{ER_T} - \mathrm{ER}_\Phi}{10}\right)\right]. \tag{5}$$

As an example, assume a total facility length of 15 kft of 26-gauge pulp cable installed at mean temperature and hence subjected to a 25°F temperature change. Computations show that

$$\mathrm{ER_T} = -27.5 \text{ dB},$$
$$\mathrm{ER}_\Phi = -37 \text{ dB},$$
$$\mathrm{ER_{TOTAL}} = -27 \text{ dB}.$$

The end-to-end *Picturephone* system echo rating objective[5] is −26 dB with −27 dB allocated to baseband transmission on loops and trunks and −33 dB allocated to all other system impairments such as switching, station sets, and codecs. Consequently, the 15 kft of 26-gauge cable installed at mean temperature uses the entire transmission echo rating allocation of −27 dB.

Since the effects of phase distortion and changing cable insertion loss due to changing temperature on echo rating are the same for loops and trunks, loop and trunk echo rating impairments add together

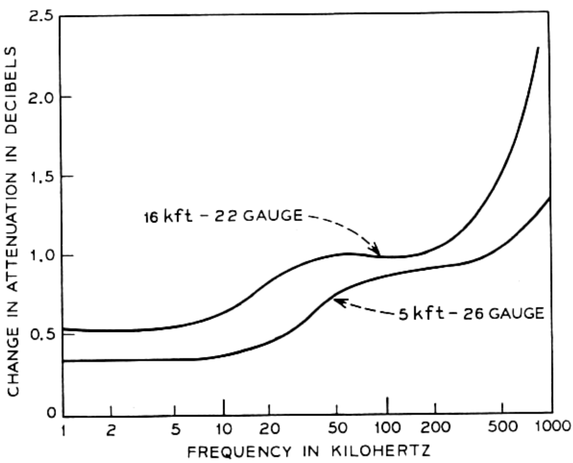

Fig. 16—Typical measured effects of temperature on cable attenuation for a 25°F temperature change.

on a voltage (correlated) basis. The transmission impairment allocation for echo rating is divided so that approximately one-third is allocated to each of the two loops and to the sum of the baseband trunks in an entire end-to-end *Picturephone* connection. Based on an echo rating[5] of −27 dB, each loop and the sum of all trunks are designed to meet a −37 dB echo rating. The resulting loop and trunk half-connection* lengths are tabulated in Tables II and III as a function

TABLE II—DESIGN LENGTH OF LONGEST LOOP*

Gauge	Length in kft† For Given Temperature Variation From Time of Alignment‡			
	50°F (No temp. realignment 1 visit)	25°F (Recommended; mean temp. 2 visits)	12.5°F (Seasonal 4 visits/yr)	2.5°F (No temp. variation 1 visit)
26	2.7 (11)§	5.1 (6)	8.8 (3)	15
24	3.7 (8)	6.9 (4)	12 (2)	18
22	9.7 (3)	16 (2)	21 (1)	24
19	14 (2)	24 (1)	31	35
16	20 (1)	37	58	78

* For present cable equalizer designs only.
† Lengths must be reduced by 10 percent per splice in cable sections placed prior to 1940.
‡ Alignment procedure based on 50°F maximum temperature variation assumed for underground cable.
§ Number in parentheses is the percentage reduction in length required per 100 feet of aerial cable, up to a maximum of 500 feet.

of gauge and temperature variation. For example, to meet a loop echo rating of −37 dB, loops are limited to 5.1 kft of 26-gauge pulp cable or 16 kft of 22-gauge cable, assuming mean temperature alignment, i.e., a 25°F temperature change on underground facilities. A trunk half-connection is limited to 10 kft of 22-gauge cable, assuming quarterly alignment to minimize temperature effects, i.e., 12.5°F temperature change on underground facilities. These allowed lengths will be increased significantly by the use of a later version of the cable equalizer with less phase distortion and with temperature regulation, i.e., from 5.1 to 15 kft for 26-gauge loops and from 10 kft to 100 kft for 22-gauge trunk half connections.

* Each end-to-end *Picturephone* connection is allowed two loops and two trunk half-connections. Each trunk half-connection has an echo rating of −43 dB.

TABLE III—DESIGN LENGTH OF LONGEST TRUNK HALF-CONNECTION*

Gauge	Length in kft† For Given Temperature Variation From Time of Alignment‡: 50°F (No temp. realignment 1 visit)	25°F (Mean temp. 2 visits)	12.5°F (Recommended; seasonal 4 visits/yr)	2.5°F (No temp. variation 1 visit)
26	1.3 (22)§	2.5 (12)	4.4 (6)	7.5
24	1.8 (17)	3.5 (8)	5.8 (4)	9.1
22	4.8 (6)	7.9 (3)	10 (2)	12
19	7.2 (4)	12 (2)	15 (1)	18
16	10 (3)	19 (1)	29	39

* For present cable equalizer designs only.
† Lengths must be reduced by 20 percent per splice in cable sections placed prior to 1940. Lengths are reduced 30 percent if baseband on TD-2 is used as one trunk facility.
‡ Alignment procedure based on 50°F maximum temperature variation assumed for underground cable.
§ Number in parentheses is the percentage reduction in length required per 100 feet of aerial cable, up to a maximum of 500 feet.

6.3 *Cable Equalizer Spacing*

Cable equalizer spacing, as opposed to total loop length discussed above, is limited by the crosstalk properties of the cable. When cable equalizers for both directions of transmission are installed at the same physical location, there is some possibility that the output of one can feed into the input of the other via cable near-end crosstalk (NEXT) paths and cause "singing." This is, of course, most likely to occur at the higher frequencies where equalizer gain must be high and crosstalk loss is low. This crosstalk situation is shown in Fig. 17 for two loops connected to the same video switching office by cable pairs within one cable sheath. The arrows indicate near-end crosstalk paths coupling the output of one cable equalizer to the input of another. The magnitude of the crosstalk problem is a function of crosstalk loss and cable equalizer gain and, hence, cable equalizer spacings.

As shown in Fig. 17, two loops, each with one ICE, have four possible NEXT paths, any one of which may cause "singing." For the maximum length loops with three ICEs, eight such paths exist. If the system objective is a 14-dB margin against oscillation 99 percent of the time at 1 MHz, then each of the eight paths should have this 14-dB margin approximately (1 − 0.01/8) or 99.875 percent of the time. An approximation is made here that one and only one of the eight possible crosstalk paths dominates for the worst case of only a 14-dB margin against oscillation. The exact analysis of this situation, which is discussed in Ref. 7 and considers the sum of all eight paths taken together, yields essentially the same result.

Assuming a log normal NEXT distribution, this 99.875 percent represents the 3σ point on the distribution. For single unit operation, the NEXT crosstalk distribution has a mean of 74 dB and a standard deviation of 8.8 dB. Consequently, the 99.875 percent point on the NEXT distribution is 74 − 27 dB or 47 dB of loss. Subtracting 14 dB for margin against oscillation gives a maximum equalizer gain of 33 dB at 1 MHz. Similar considerations for adjacent unit operation give a maximum equalizer gain of approximately 54 dB at 1 MHz. Consequently, the maximum cable equalizer spacings may be from 3.6 to 5.8 kft for 26-gauge cable pairs or from 4.9 to 8.0 kft for 22-gauge cable, depending on which cable pairs are used, i.e., whether the pairs for the opposite direction of video transmission are in the same unit or adjacent units. Special circumstances, like high impulse noise levels coupled through NEXT paths from audio pairs to video pairs, may dictate shorter spacings.

A tabulation of the maximum equalizer spacing for opposite directions of video transmission in the same unit and separate units is shown in Table IV for various cable gauges. Since cable NEXT loss is limiting for same unit and adjacent unit operation, one would

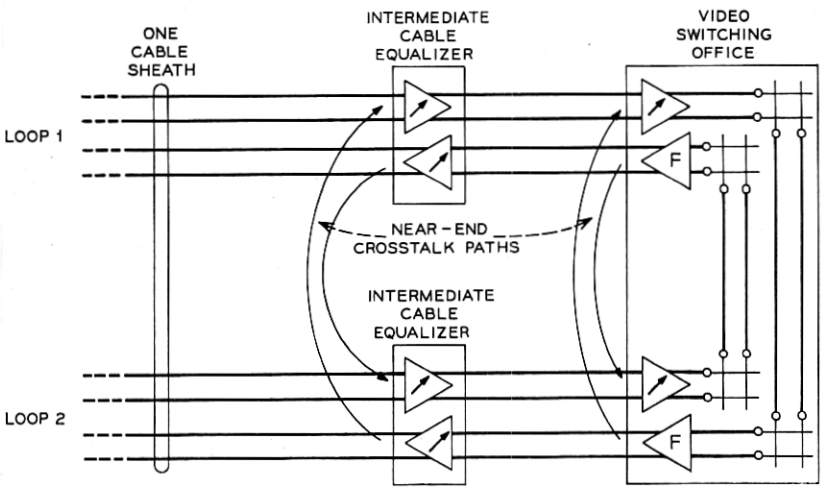

Fig. 17—Effect of cable near-end crosstalk on cable equalizer spacing.

TABLE IV—MAXIMUM LOOP EQUALIZER SPACINGS*

	Opposite Directions of Video Transmission in:	
Gauge	Same unit (kft)	Separate unit (kft)
26	3.6	5.8
24	4.1	6.7
22	4.9	8.0
19	7.3	12
16	—	27

* If steam pipes should parallel a route, reduce spacings by 7 percent; if layer-type cable, reduce by 15 percent.

normally expect that if nonadjacent units or separate sheaths were used, a greater equalizer spacing would be possible. However, available cable equalizer gain as discussed in Section IV limits equalizer spacings to the same numbers derived on the basis of adjacent unit NEXT for 19-, 22-, 24- and 26-gauge pulp cables. For 16-gauge cable, which consists of individually shielded pairs, cable equalizer spacing is limited by the maximum equalizer gain capability and not by crosstalk considerations.

6.4 *Pair Selection and Installation of Cable Equalizers*

For the first step in providing video pairs for *Picturephone* service, it is recommended that entire cable units or complements be chosen, using assignment and cable records, in accordance with the video transmission engineering rules discussed in Section 6.1. Because of the complexity involved in selecting and conditioning video pairs, it is not economically feasible to select just one pair at a time as the demand arises, but rather entire complements in anticipation of *Picturephone* demand. Reserving pair complements for *Picturephone* service does not mean that these pairs can be used only for video, but that the temporary use of these reserved pairs for other systems must be compatible with the engineering rules. The choice of a cable route to provide *Picturephone* service may not be the shortest route; the economics may be such that the total cost of the shortest route, including cable plus conditioning may exceed the total cost of a longer route which requires less conditioning.

The selected complements must then be "conditioned" for video transmission. Conditioning includes, for example, cable rearrangements necessary to remove incompatible systems, such as T or N carrier, from the chosen complements and the removal of all load coils, build out capacitors, and excessively long bridged taps from pairs selected for video transmission.

It is necessary to verify the pair acceptability by performing measurements on at least a representative sample of pairs within a complement. The standard tests used for telephone service are performed first and include dc tests for insulation resistance and foreign EMF. Additionally, low frequency longitudinal and transverse noise tests are made. These noise tests are important to insure that the levels of 60-Hz pickup and harmonics thereof do not exceed the allowable levels as discussed in Section III and Ref. 5.

The last step in determining the pair acceptability is to determine whether unrecorded bridged-taps, load coils, and other sources of impairments are present. The presence of such impairments is most easily determined by equalizing the selected cable pairs by means of a cable equalizer packaged within a portable test set. Gross transmission impariments result in the inability to align a cable section at the six alignment frequencies. The presence of a load coil which essentially inhibits transmission above 4 kHz is one example of a gross impairment. Less severe impairments may permit the equalization of a cable section at the six frequencies but still result in unacceptable performance because of ripples in the amplitude response between alignment frequencies. Bridged-taps, build-out capacitors, and parafin splices may cause these ripples in the amplitude response. The presence of such ripples is determined by making a swept frequency measurement between the highest alignment frequencies of 500 kHz and 900 kHz.

If cable pairs chosen for video transmission do not pass the pair suitability tests outlined above, either alternate pairs are chosen or the source of impairment must be located and corrected. To locate a source of ripple impairment, a commercially available pulse echo test set is used to measure the time delay between the main transmitted pulse and the returned echo and hence the distance to the impairment. Because of the loss of cable pairs at frequencies up to 1 MHz, pulse echo tests may have to be made from both ends of the cable pairs.

After choosing the pairs for video transmission, conditioning them, and verifying their acceptability, the cable equalizers are then installed and aligned. Prior to placing the equalizers in their respective housings along the video pairs, the various screw switch settings and plug-in networks are chosen and set. Then the potentiometers are adjusted with the cable equalizers in place and working. The test set shown in Fig. 13 is used to align the cable equalizers. The recommended method of alignment requires a craftsman with a test set simultaneously at each cable equalizer location along a video pair. An order wire allows voice communication among the various locations.

VII. MAINTENANCE FEATURES

Prior to the completion of a *Picturephone* call, a continuity test is performed by the video switching office on video loops.[2,8] A 12-kHz signal is transmitted from the switching office and is returned to the office via a loopback within the station set, PBX, or KTS. This loopback is removed by an off-hook condition at the station set and by the detection of a sync signal transmitted from the switching office to the station set, PBX, or KTS.

The quality of loop equalization may be checked using the loopback feature. Broadband test signals transmitted from the test center[8] at a switching office are returned to the office via the loopback, thereby allowing the quality of video transmission to be determined for both directions of transmission in tandem. Such a test cannot isolate troubles to one of the two video pairs or to a particular section of cable.

A fault locating network (FL1 and FL2 of Fig. 18) contained in the central office and intermediate cable equalizers allows the selective interrogation from the central office of a particular cable equalizer in order to determine if catastrophic cable equalizer failure has occurred.

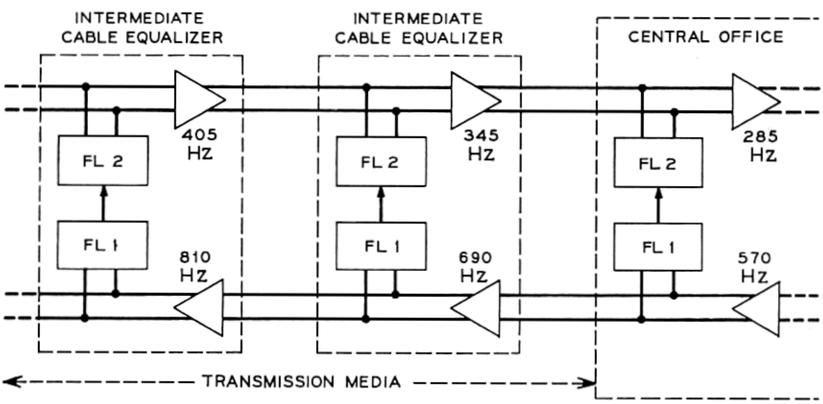

Fig. 18—Fault location.

The fault locating network in the outgoing cable equalizers contains a filter tuned to one of four audio frequencies in the range from 500 Hz to 1000 Hz, which allows the selective interrogation of a particular cable equalizer. A Schmitt trigger is actuated if the filter output is of sufficient amplitude. The complementary incoming cable equalizer contains a bistable multivibrator which is triggered by every other pulse obtained from the differentiated output of the Schmitt trigger. The multivibrator output, a square wave of frequency one half the interrogating frequency, is then transmitted back to the central office on the incoming video pair. Detection of this half frequency signal at the central office indicates that a particular section of the loop has no gross impairment at low frequency. This test cannot be used to detect a degradation of the high frequency amplitude response.

If the dc current flowing in the video pairs for powering intermediate cable equalizers is interrupted, the fault-locating network will be inoperative. But it is possible to localize the failure to a particular section by removing the central office cable equalizers and applying a 48-volt supply as shown in Fig. 19. This causes dc current to flow in the direction opposite to that of the loop powering current. The reverse voltage across the two video pairs at an equalizer causes a diode to conduct current from one video pair to the other through a resistor. The amount of loop current flowing gives an indication of the

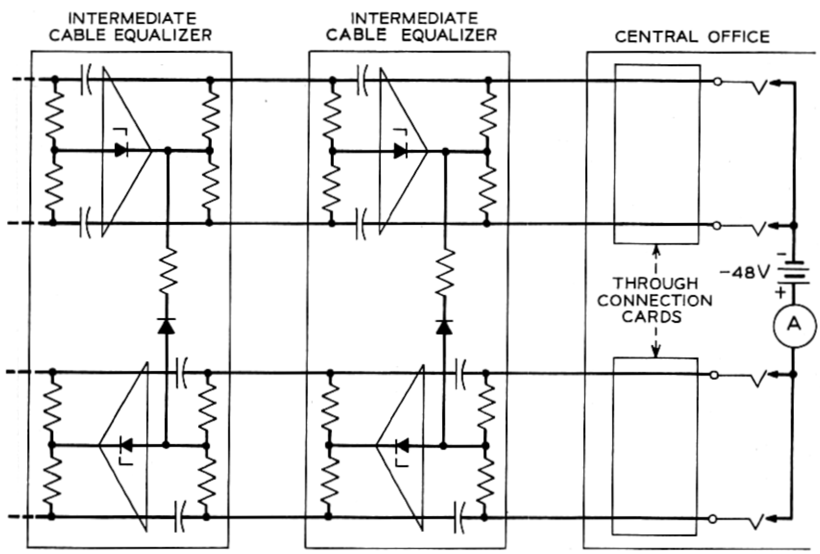

Fig. 19—Arrangement for locating open circuits in the video path.

number of bridging resistors and hence the number of "good" sections by counting toward the station set from the central office. This test will provide no useful information if only one conductor of the video pair is open since this dc test current can still flow, causing additional resistors to be bridged across the video pairs which indicate "good" sections. In addition, this test for locating open circuits may not be used if ICEs are locally powered.

VIII. SUMMARY

A means for providing baseband video transmission on customer loops and on short haul trunks using present telephone cable facilities has been described. A cable equalizer which provides adjustable shaped gain up to a maximum of 54 dB at 1 MHz is required approximately every mile. Special procedures will be required to condition the telephone pairs for video transmission.

IX. ACKNOWLEDGMENTS

Numerous people have contributed to the design of the baseband video transmission system described in this paper. In particular, the author wishes to acknowledge the electrical design contributions of S. J. Brolin, L. C. Sanders, H. C. Bond, and R. J. Welborn, assisted by J. H. Beck, R. R. DeSimone, and T. A. Sickman; the physical design contributions of F. H. King, W. C. Jurgens, and R. R. Fornilli; the system computer simulation contributions of F. L. Schwartz, F. M. Stumpf, and Mrs. A. F. Rogers; the system engineering contributions of G. W. Aughenbaugh; and the work of R. S. Farbanish and G. E. Harrington on pair acceptability testing.

REFERENCES

1. Cagle, W. B., Stokes, R. R., and Wright, B. A., "The *Picturephone*® System: 2C Video Telephone Station Set," B.S.T.J. this issue, pp. 271–312.
2. Burgess, P. N., and Stickel, J. E., "The *Picturephone*® System: Central Office Switching," B.S.T.J., this issue, pp. 533–552.
3. Daskalakis, A., "The *Picturephone*® System: Key Telephone Systems," B.S.T.J., this issue, pp. 567–584.
4. Anderson, H. P., "The *Picturephone*® System: 850A PBX," B.S.T.J., this issue, pp. 585–604.
5. Brown, H. E., "The *Picturephone*® System: Transmission Plan," B.S.T.J., this issue, pp. 351–394.
6. Crater, T. V., "The *Picturephone*® System: Service Standards," B.S.T.J., this issue, pp. 235–269.
7. Bunin, B. J., Hirsch, R. B., and Olsen, R. E., "The *Picturephone*® System: Crosstalk Considerations in the Transmission of Analog Signals on Paired Cable," B.S.T.J., this issue, pp. 427–457.
8. Doughtery, H. J., Peterson, E. B., and Schachtman, M. G., "The *Picturephone*® System: Maintenance Plan," B.S.T.J., this issue, pp. 621–644.