Crosstalk and Noise Features of Cable Carrier Telephone System *

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CROSSTALK and noise are important factors in cable carrier transmission as outlined in the paper "A Carrier Telephone System for Toll Cables" by Messrs. C. W. Green and E. I. Green. Crosstalk and noise limit the number of carrier channels which can be utilized in any one cable, not only by limiting the number of channels which can be placed on a single pair, but by limiting the number of pairs which can be used. Noise also controls the transmission loss which can be permitted between repeaters. Without the crosstalk and noise reduction measures described in this paper, the number of carrier channels per cable would be so few and the spacing between repeaters so short, that the type K carrier system would be impracticable.

Crosstalk

To utilize existing toll cables in the Bell System for frequencies up to 60 kilycycles required the solution of many new crosstalk problems because: (1) Crosstalk increases rapidly with the frequency, (2) Non-loaded carrier pairs due to their high speed of propagation are especially suitable for very long distances and hence the crosstalk requirements per unit length are relatively severe, (3) The large gains of the carrier repeaters amplify certain crosstalk currents much more than in the case of voice frequency circuits.

Two general effects need to be considered: intelligible crosstalk must be prevented; and, a large number of circuits crosstalking into a particular circuit must not contribute an undue amount of noise. The second effect is called babble, since it consists of a multiplicity of unrelated voice sounds which, in the aggregate, are unintelligible.

An important feature is the use of different cables for opposite directions of transmission. This makes the major crosstalk problem the reduction of crosstalk between pairs in the same cable used for transmission in the same direction. The crosstalk currents due to transmission at one end of a disturbing circuit through the distributed couplings with a disturbed circuit tend to arrive at the distant end at the same time since the currents via any of the couplings travel sub-

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stantially the same distance. This makes it possible to greatly reduce the total effect of these distributed couplings by the use of small adjustable mutual inductance coils connected between pairs at one point in each repeater section.

If nothing more were done, there would still be objectionable crosstalk since currents from the outputs of carrier repeaters could crosstalk into voice frequency circuits and these circuits could then again crosstalk into other carrier frequency circuits at points near their repeater inputs. This effect is minimized by transposing the carrier pairs from one cable to the other at carrier repeater points.

At common voice frequency and carrier frequency repeater points there would be an unsatisfactory crosstalk path from a carrier repeater output into all the wires not used for carrier frequencies and from them through coupling between office wiring into similar wires in the other cable and finally into carrier repeater inputs in the second cable. This crosstalk is minimized by the use of carrier frequency suppression coils in the voice frequency circuits. These coils also serve the purpose of preventing carrier frequency noise originating in voice frequency circuits from being transmitted into the cables and inducing noise at points near carrier repeater inputs.

Near-End Crosstalk

Near-end crosstalk is the result of coupling between circuits transmitting in opposite directions, while far-end crosstalk is the result of coupling between circuits transmitting in the same direction. Near-end crosstalk coupling between different carrier circuits of the same frequency must be kept very small, particularly near a repeater point, since crosstalk from the output of a repeater into an opposite directional pair near the input of its repeater will be greatly amplified by this repeater.

Crosstalk between carrier circuits within the offices is kept low by careful shielding, segregation, suppression of spurious paths through battery supply, common grounding arrangements, etc.

Since the type K system operates on a "four-wire" basis, different electrical paths are used for opposite directions of transmission. Satisfactory near-end coupling in the outside plant is obtained, therefore, by placing east bound pairs in one cable and west bound pairs in another. When two cables have relatively heavy sheaths as in the larger Bell System cables, their coupling is sufficiently small even with the two cables in close proximity.

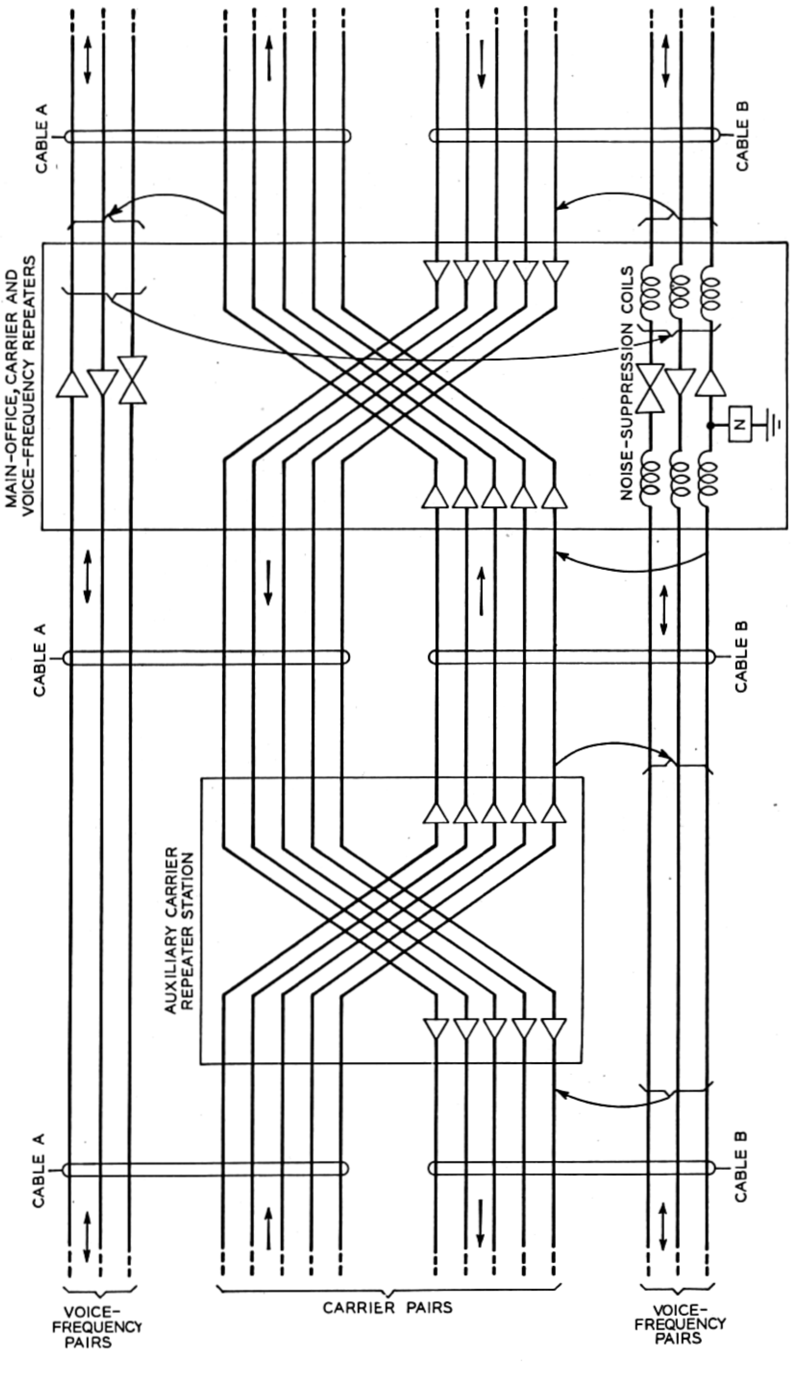

Fig. 1—Schematic showing carrier pairs transposed between cables, coupling paths and noise suppression coils.

Interaction Crosstalk

The crosstalk currents from a carrier repeater output into voice frequency circuits in the same cable must be limited, since they crosstalk again into carrier circuits near repeater inputs and, consequently, are amplified by the high gain repeaters. Intermediate circuits most responsible for crosstalk of this type are made up of combinations of pairs and phantoms and the sheath, i.e., longitudinal paths.

One case of crosstalk of this kind would occur if the same cable were used for carrier pairs transmitting in the same direction on both sides of a repeater. This is prevented by transposing carrier pairs from one cable to the other at each repeater point, as shown on Fig. 1.

A second interaction crosstalk problem is encountered at the common voice and carrier repeater points and involves coupling between cables as well as in the same cable. Here the coupling path is from carrier repeater outputs to intermediate circuits in the same outside cable, back into the common office over these intermediate circuits and then via office coupling to intermediate circuits in a second outside cable and from there to carrier repeater inputs connected to pairs in the second cable. Referring to Fig. 1, a set of noise (and crosstalk) suppression coils is encountered in this path. The high longitudinal circuit impedance of these coils minimizes this interaction crosstalk.

Far-End Crosstalk

Far-end crosstalk currents are subjected to line attenuation and amplification similarly to the main transmission currents, and do not have extra amplification as in the case of near-end crosstalk. Furthermore, far-end crosstalk currents due to couplings at different points along the line tend to arrive at the distant end of the disturbed circuit at the same time. Hence a considerable portion of the far-end crosstalk over the type K frequency range, which occurs between circuits transmitting in the same direction in the same cable, can be neutralized by introducing compensating unbalances at only a comparatively few points, such as one per repeater section. The far-end crosstalk reduction problem is greatly simplified because phantom circuits are not used for carrier operation.

Theoretically, for the same precision of match between the impedances in the two directions at the balancing point, the crosstalk reduction would be about the same whether the balancing is done at an intermediate point or at either end of a repeater section. Balancing will be done at repeater inputs rather than at an intermediate point, such as the middle, because it is practicable to obtain repeater impedances matching the average line impedance sufficiently well so that the effectiveness of balancing is reduced only slightly.

Nature of Far-End Crosstalk Coupling

The coupling between two cable pairs in a short length may be represented by a mutual admittance and a mutual impedance. The former is due almost entirely to capacitance unbalance, which varies but little with frequency, so that its effect could be practically balanced out by means of a simple condenser. The latter, however, involves a complex mutual inductance of the form $M_a + jM_b$, because of the proximity effect of the wires of a pair and of other cable conductors.[1] As shown on Fig. 2, both components vary considerably with fre-

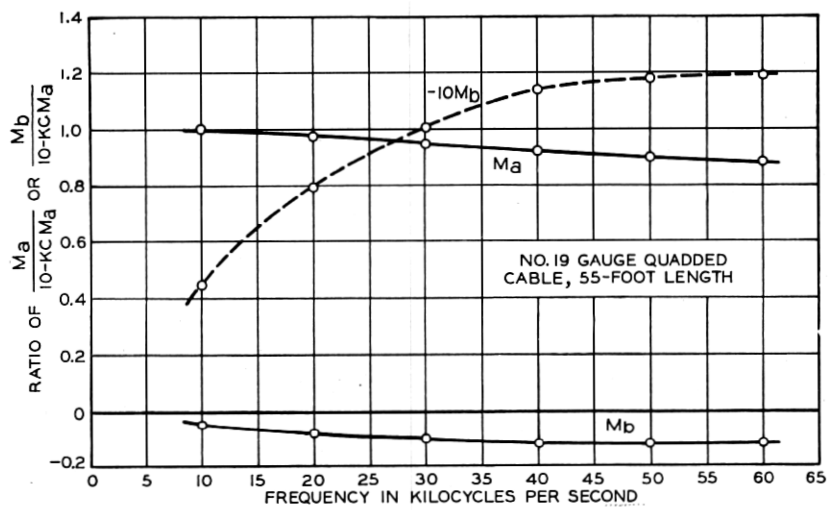

Fig. 2—Mutual inductance between cable pairs in terms of value for M_a at 10 kilocycles.

quency; M_a on the average decreasing as the frequency increases while M_b in the general case is of negative sign and reaches a maximum value at 56 kilocycles.

Type of Balancing

To obtain maximum reduction in crosstalk it would be necessary to use a condenser for balancing the mutual admittance and an inductance coil for balancing the mutual impedance or to use some equivalent complex network. Experimental balancing in a particular cable using the coil-condenser method reduced the mean crosstalk over the type K

[1] "Cable Crosstalk—Effect of Non-Uniform Current Distribution in the Wires," R. N. Hunter and R. P. Booth, *Bell System Technical Journal*, April 1935.

range about 20 db, which is close to the maximum reduction possible with a universal type of balancing unit. The reduction is limited by the fact that two pairs having identical crosstalk couplings in each of two short lengths at different points in the cable will not produce two identical elements of crosstalk current at a circuit terminal because: (1) Cable circuits are not perfectly smooth. Reflections, as at junctions of reel lengths or at terminals, alter the two crosstalk currents differently, (2) The propagation constants of each circuit vary slightly from reel to reel in a random fashion and therefore the two crosstalk currents are of slightly different phase and magnitude, (3) In any short length the disturbing circuit produces crosstalk currents in intermediate circuits, which are propagated along these circuits and crosstalk again into the disturbed circuit at various points, producing an additional crosstalk current at the circuit terminal. At any frequency, this interaction crosstalk current has a random phase and magnitude relation to the crosstalk current for the short length considered by itself, and depends also upon the position in a repeater section of the short length.

A 20 db crosstalk reduction is not required, considering the number of K systems anticipated in any one cable. Studies were made, therefore, to determine whether satisfactory results could be obtained with a less expensive type of balancing, as outlined below.

The effects of frequency and circuit impedance on crosstalk coupling are as follows: (1) Crosstalk in a short length due to capacitance and to inductance coupling increases about directly as the frequency increases for circuits whose impedance is independent of frequency. (2) Crosstalk due to capacitance coupling varies directly as the impedance of the circuits while that due to inductance coupling varies inversely as the impedance. Changing the impedance from about 800 ohms for loaded voice circuits to about 135 ohms for non-loaded carrier circuits and changing the frequency from about 4 kc. to 60 kc. increases the crosstalk due to capacitance coupling by a factor of about 2.5 and that due to inductance coupling by a factor of about 90.

Capacitive coupling in existing cables was reduced by design to as great a degree as practicable, particularly for the most closely associated circuits, because it is of most importance in the loaded voice frequency case. These same design measures also reduce inductive coupling but not to the same extent. Capacitive coupling decreases rapidly with separation due to the shielding effect of copper in intervening circuits while inductive coupling is not much affected by intervening copper wires. To minimize magnetic coupling it is necessary to use different lengths of twist for the pairs. Existing cables have relatively few lengths of pair twists.

As the net result, capacitance coupling is no longer all important, inductance coupling at 60 kc. actually predominating by a factor of about 3 to 1 in existing cables. Capacitance balancing should, therefore, be less effective than balancing designed to reduce the inductance coupling. Tests have shown that capacitance balancing alone gives a crosstalk reduction of about 11 db while inductance balancing alone gives a reduction of about 16 db. Since the latter reduction is sufficient, except possibly for small cables or special cases, the type K balancing has been designed on this basis. Far-end crosstalk currents due to the two kinds of coupling have phase relations not differing from zero or 180 degrees by more than about 15 to 40 degrees, depending on whether the upper or lower type K frequencies are considered. There is, therefore, a tendency for either type of balancing unit to annul both kinds of coupling.

To obtain as much as 16 db reduction it is necessary that the frequency characteristic of the balancing coil simulate that of the cable (Figure 2). This was found practicable, as discussed later, by shunting the primary (or secondary) of the coil by a properly designed impedance.

Size of Balancing Coil

To meet the crosstalk requirement it is necessary to balance each carrier pair against every other carrier pair. If 50 carrier pairs were used, there would be 49 balancing coils connected to each pair for balancing to all the other pairs, a total of 1225 coils. For convenience, adjustable coils having the same mutual inductance range and the same self-inductance are used. Hence, the insertion loss per coil, resulting from the self-inductance and resistance of the coils, must be kept small. In addition, the self-inductance of the coil presents a problem from the impedance standpoint. To keep the impedance at any point in the balancing panel as nearly like the average cable impedance as practicable, the self-inductance of a series of coils must be neutralized by capacitances shunted at suitable intervals. It is very desirable, therefore, to use coils whose self and mutual inductances are no larger than actually essential. Consequently, an attempt has been made to keep the maximum crosstalk before balancing low.

Due to special measures, described below, it appeared that the maximum inductance unbalance per repeater section could be kept below about 1.3 to 1.5 microhenries, with the possible exception of side-to-side unbalances, and trial balancing coils were designed accordingly.

Crosstalk Reduction Before Balancing

Changes in the original splicing are made at approximately 6000-foot intervals, i.e., at points where voice frequency loading coils must be removed from the carrier pairs. In most existing voice frequency toll cables the 19-gauge quads were spliced as three groups, one a two-wire circuit group, one an east bound four-wire circuit group and the third a west bound four-wire circuit group. Ordinarily, the carrier pairs will be selected from the four-wire groups because these groups are usually larger than the two-wire group and since the quads within a group are spliced at random there is less chance of a large value of coupling between pairs of different quads, i.e., two pairs are less apt to be recurrently in a relation of high coupling. The carrier pairs are divided equally between the two four-wire groups, in order that the least number of four-wire voice circuits will be lost.

In cables with large four-wire groups it is satisfactory to maintain the grouping arrangement on the pairs converted to carrier. In such cables, however, one four-wire group is in the center or core of the cable and the other group in the outer periphery. In order that all circuits will have about the same velocity and attenuation and be subjected to about the same temperature conditions for both transmission and crosstalk reasons, one (four-wire) carrier group in these cables will be spliced to the other (four-wire) carrier group and vice versa at the 6000-foot intervals.

In cables with relatively small four-wire groups, there is more chance of two pairs being recurrently in a relation of high coupling. To reduce this chance, a special splicing arrangement has been devised for use at the 6000-foot intervals. With existing splicing the maximum coupling in cables with small groups is about 2.5 times that for cables with large groups. This ratio is appreciably reduced by the special splicing, likewise reducing the maximum mutual inductance that must be supplied by the balancing unit.

The foregoing was with particular reference to crosstalk between pairs in different quads. Crosstalk between pairs in the same quad (side-to-side crosstalk) is an additional problem. A quad consists of two twisted pairs of wires which are twisted together to permit the use of voice frequency phantom circuits. Since the two sides of a quad are so closely associated, side-to-side crosstalk is generally much greater that than between pairs of different quads. The electrical size of the balancing unit, therefore, is determined by the side-to-side crosstalk, which is reduced by "poling."

To apply poling, the quads are carried through as quads for an entire carrier repeater section. From measurements of side-to-side crosstalk in phase and magnitude, quads in one half repeater section are chosen and spliced to quads in the other half in such manner as to partially neutralize the side-to-side crosstalk. In effect, quads in one half-section serve as balancing units for the other half.

In most existing toll cables the side-to-side capacitance coupling was reduced when the cables were installed, by means of test-splicing within the 6000-foot sections. Obviously, for poling to be effective it is necessary to operate mainly on the inductance component. The poling measurements, therefore, are made at about 1 kc. where an approximate measure of the inductance component can be obtained directly since the capacitance and inductance components of the crosstalk are at an angle of almost 90° at this frequency. Figure 3 shows the crosstalk results obtained by means of 1-kc. poling on 14 repeater sections. It has been shown that this 9 db reduction is within 2 to 3 db of the

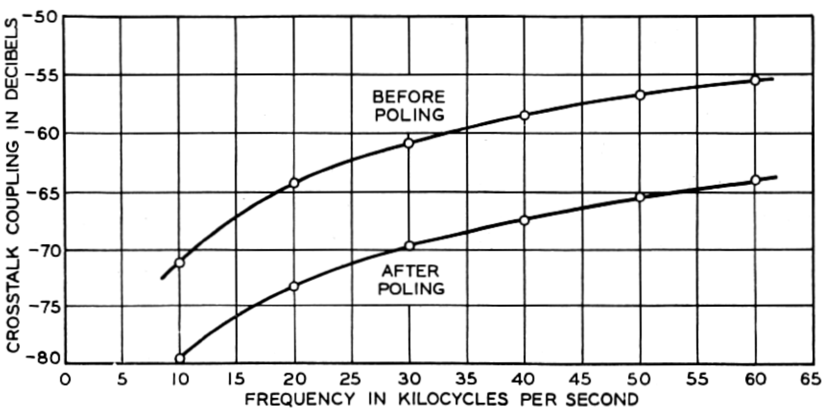

Fig. 3—R.M.S. side-to-side far-end crosstalk per repeater section from measurements on 14 repeater sections.

maximum reduction possible with much more complicated poling involving measurement and consideration of both components at carrier frequencies.

After side-to-side poling, coil balancing cannot be expected to give as much as 16 db reduction in crosstalk. This is unimportant, however, as long as the required reduction can be obtained more economically by the combined methods rather than by balancing alone.

Crosstalk Balancing Coil

Since the voltage which causes the crosstalk current in the disturbed circuit may be in either a clockwise or counter-clockwise direction, the balancing device, for flexibility reasons, should be capable of establishing voltages in either direction. A balancing coil was developed, therefore, which in operation may be likened to that of two separate transformers with simultaneously movable cores. The primary windings are in series, as are the secondary windings, and are connected as shown in Fig. 4, for example. The relative direction of each secondary winding is the same, whereas the relative directions of the primary windings are reversed. With the cores in mid-position, the voltages induced in the two secondaries are equal in magnitude but opposite in phase, and the net induced voltage in the disturbed circuit is zero. As the cores are moved toward the left the respective components of the voltage induced in circuit 3–7–8–4 increase in a counter-clockwise direction and decrease in a clockwise direction, the net result being a voltage in a counter-clockwise direction. Such a setting of the balanc-

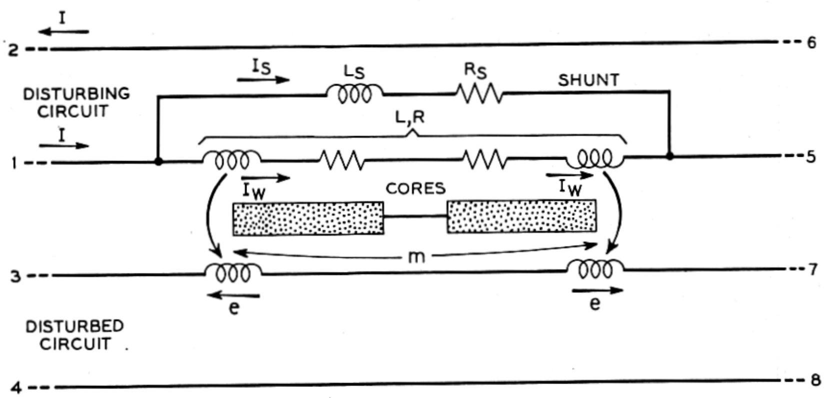

Fig. 4—Schematic of a simple balancing coil designed to produce a complex mutual impedance.

ing coil would be used to counteract a clockwise crosstalk voltage, the amount of departure of the cores from mid-position being dependent on the magnitude of the crosstalk voltage being counteracted. Movement of the cores toward the right produces the opposite effect.

This device, disregarding any proximity effects therein and the effects of the shunt, acts to set up a net voltage e which is in phase quadrature with the disturbing current I. Hence,

$$e = -j\omega m I, \tag{1}$$

in which m is the net mutual inductance of the device. To obtain the required mutual impedance characteristic, the primary (or secondary) windings of the coil are shunted by an inductive resistance. Let the effective self-inductance and resistance of the line windings (primaries) be denoted by L and R, respectively, and the current through these windings by I_w. Let the effective self-inductance and resistance of the shunt be denoted by L_s and R_s, respectively. At balance, that is, when no crosstalk current flows in 3–7–8–4 due to I (the disturbing current), the current I_w is

$$I_w = \left[\frac{R_s(R + R_s) + \omega^2 L_s(L + L_s)}{(R + R_s)^2 + \omega^2(L + L_s)^2} - j\frac{\omega(R_s L - RL_s)}{(R + R_s)^2 + \omega^2(L + L_s)^2} \right] I \quad (2)$$

$$= [a - jb]I, \quad (3)$$

where a and b are, respectively, the coefficients of the real and imaginary parts of the expression. Hence, with a shunted coil the voltage induced in the disturbed circuit is:

$$e = -j\omega m I_w = -j\omega(ma - jmb)I. \quad (4)$$

The mutual impedance, Z_m, equals $j\omega(ma - jmb)$, or the effective mutual inductance M of the balancing coil may be written

$$M = M_a + jM_b, \quad (5)$$

wherein $M_a = ma$ and $M_b = -mb$. Assuming R, L, L_s and R_s to be constant with respect to frequency of current and position of the cores, it is seen from (2) and (5) that for any core setting, M_a and M_b are functions of frequency only and their ratio at a given frequency is theoretically constant throughout the operating range.

To keep inductance L constant irrespective of the mutual inductance settings, the length of the coil windings, the length of the magnetic cores and their spacing with respect to the winding spacing are so related that the change in inductance of one primary (or secondary)

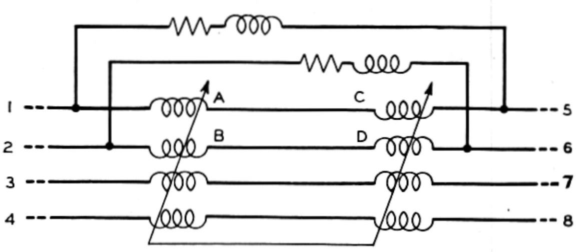

Fig. 5—Schematic of winding arrangement of trial balancing coil.

winding caused by motion of its associated core is equal and opposite to the change caused by the movement of the core associated with the other primary (or secondary) winding. To keep R low over the type K frequency range, cores of finely powdered molybdenum permalloy pressed into a cylindrical form are used.

Because of other requirements which a balancing coil must satisfy, the winding arrangement actually employed is shown in Fig. 5. The simple device of Fig. 4 is not balanced from the standpoint of longitudinal crosstalk for any coil setting except that of zero mutual inductance. The Fig. 5 arrangement is such that theoretically there is no magnetic coupling between the two circuits for longitudinal currents in either one, regardless of the coil setting. Unless the capacitance between primary and secondary windings can be kept very small, the resultant admittance unbalance produces crosstalk which is not com-

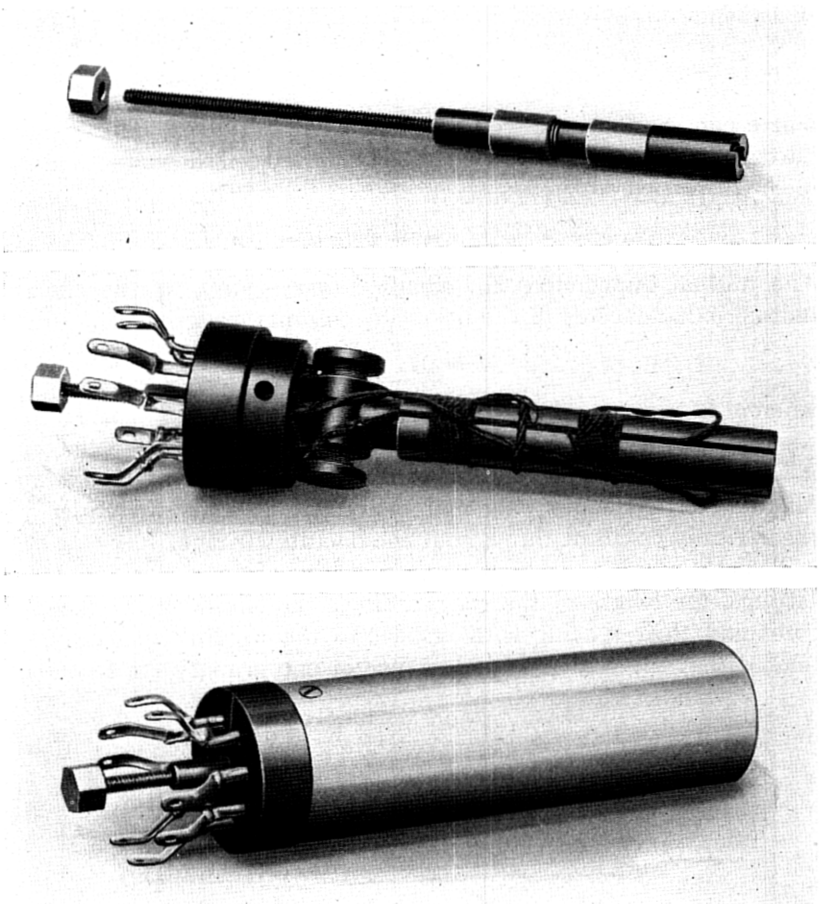

Fig. 6—Trial balancing coil construction. Container is 4½″ in length and 1⅜″ in diameter.

pletely balanced out when the coil is adjusted. The turns of conductor in the Fig. 5 coil are so located that this side-to-side capacitance unbalance is less than 5 micro-microfarads. The capacitances between wires of either the primary or secondary winding do not affect the unbalance but contribute a part of the capacitance loading which compensates for the line inductance of the coils.

In the actual balancing coil, shown in Fig. 6, the windings are located in channels cut in a fibre tube which is secured to a head carrying the winding terminals and a bushing through which passes the threaded brass rod supporting the two cores. Below the head are small spool

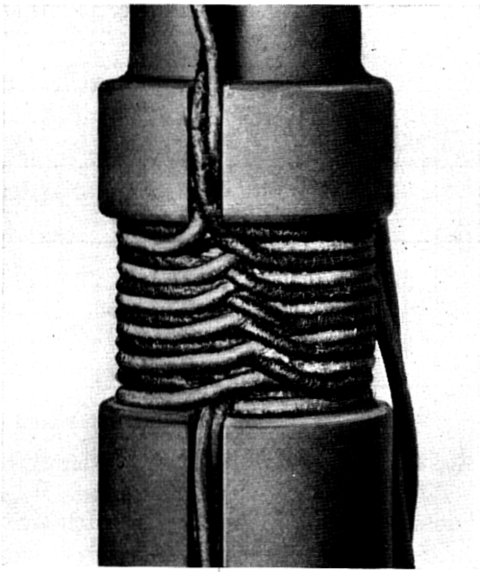

Fig. 7—Arrangement of inner winding of trial balancing coil.

forms on which the shunts are wound. Insulating material such as bakelite is used to obtain proper spacing of the two cores.

The rather unusual manner in which the turns are applied is illustrated in Fig. 7, which is a closeup view of the two wires forming the inner winding. These two wires alternately cross over each other, progressing along the axis in opposite directions of rotation. The outer winding is similarly applied. This type of winding eliminates all splices within the coil, removing hazards incident to interior splices.

The complete coil assembly is enclosed by an aluminum container which serves the dual purpose of a shield and a convenient means of holding the coil for mounting purposes as this container fits snugly into an aluminum cup riveted to the assembly panel. The windings are dried and impregnated and the space between the coil assembly and container is filled with insulating compound.

The mutual inductance of a typical coil varies as shown in Fig. 8 as the cores are moved. The range, with the shunts disconnected, is approximately + 1.6 to − 1.6 microhenries, which is covered in about 16 turns of the screw (a total core travel of 0.5 inch). With the shunts connected, the effective mutual inductance at a given setting becomes less as the frequency rises, the two components, M_a and M_b, varying with frequency as shown in Fig. 9. To determine the proper values of L_s and R_s for the shunt, allowance must be made for the complex mutual inductance inherent in the coil due to proximity effect within the windings.

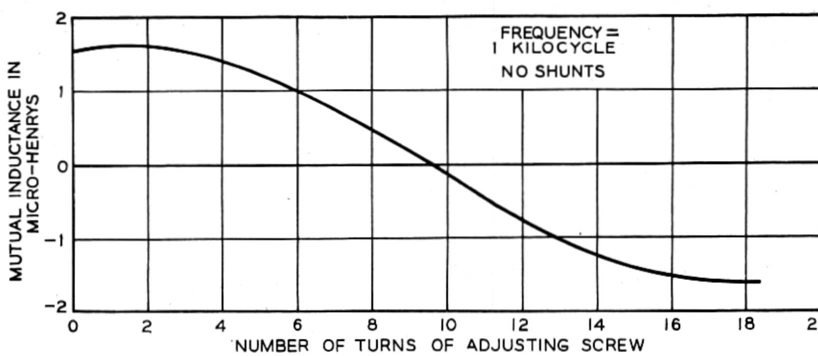

Fig. 8—Mutual inductance of trial balancing coil.

The series inductance of the balancing coil without shunts varies as shown in Fig. 10. As the cores are moved, the inductances of windings 1–*A*–*B*–2 and 5–*C*–*D*–6 (Fig. 5) behave as shown by their respective curves, one increasing as the other decreases. The sum of these two curves is shown by the dotted line, and the measured value of 1–5–6–2 is shown by the solid line. It is seen that the overall self-inductance of 1–5–6–2 is constant to within ± 0.1 microhenry. The difference between the curves (about 0.1 microhenry) is caused by the slight mutual inductance existing between winding 1–*A*–*B*–2 and 5–*C*–*D*–6, which is negative owing to reversed winding direction in this side of the balancing coil. The measured inductance around 3–7–8–4 would slightly exceed that obtained by adding the inductances of the two sections owing to positive mutual inductance between the two ends. These end effects could be reduced by greater separation of the two sets of windings, but this refinement is not necessary.

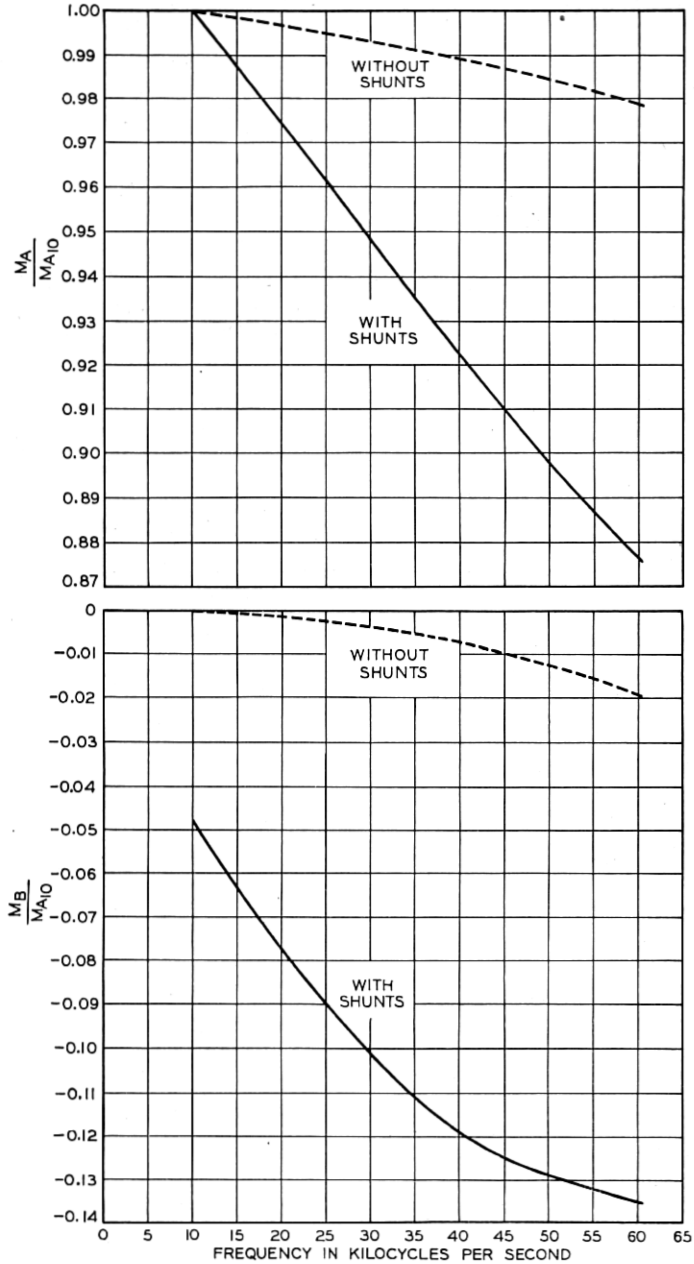

Fig. 9—Variation of M_a and M_b components of trial balancing coil with frequency.

When the shunts are connected, the inductance around 1–5–6–2 is lowered slightly, and the effective resistance is increased. To simplify the capacitance loading and in order not to introduce more resistance in one cable pair than another, the balancing coil assembly is so arranged that shunted and non-shunted windings are alternately introduced into a pair.

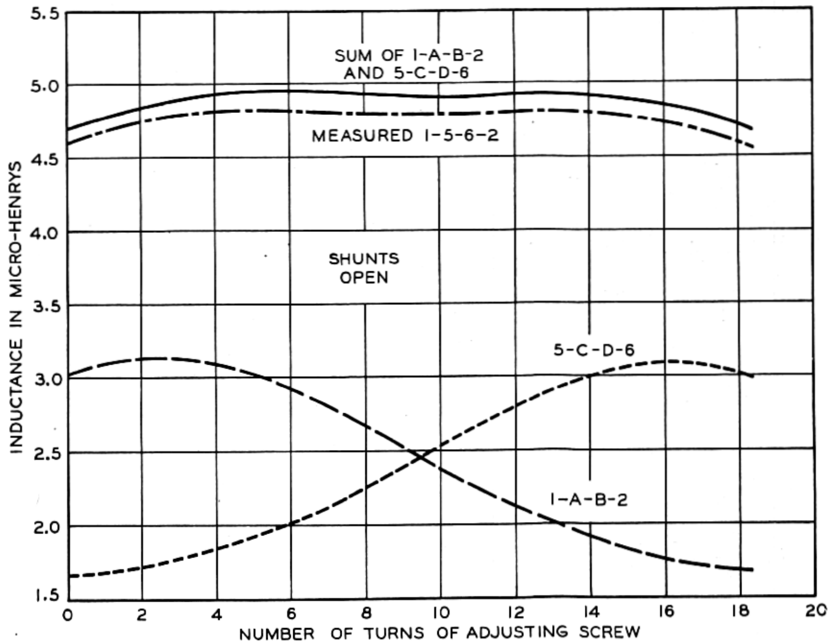

Fig. 10—Series inductance of non-shunted trial balancing coil.

Balancing Panels

In assembling the balancing coils on panels, the same number of coils should be traversed on each of two pairs before reaching the coil that balances these two pairs, in order that the phase shift up to this balancing coil on one pair will be essentially the same as that on the other pair. If these phase shifts differed materially, the coil setting for minimum crosstalk when one pair is the disturbing circuit might be quite different from the best setting when the other pair is the disturbing circuit. To obtain this equality objective a "criss-cross" arrangement, as shown schematically on Fig. 11, was devised, whereby the number of coils on one pair up to a particular balancing coil never differs by more than one from the number of coils on the other pair up to this same balancing coil.

For economic reasons it is undesirable to install a complete panel for the ultimate number of pairs, possibly 100 in some cases, but rather to install sections conforming more closely to the circuit growth. The placing at different times and properly connecting of sections obtained from the 100-pair criss-cross panel and at the same time maintaining service on operating circuits appeared rather formidable. This problem was solved by the use of two types of criss-cross panels; an

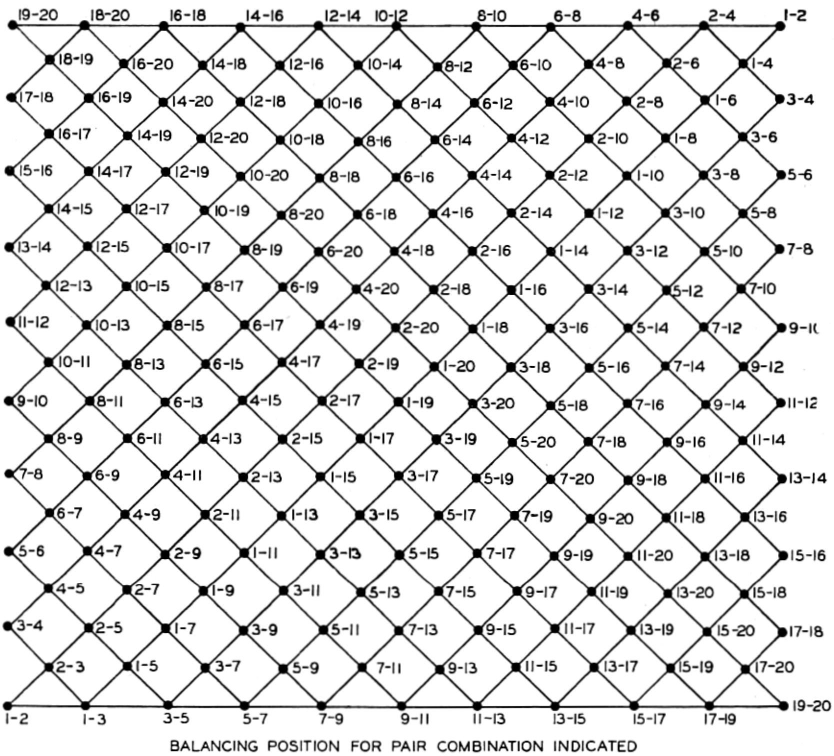

Fig. 11—Schematic of criss-cross wiring for 20-pair balancing panel, designed to maintain phase equality of coils.

intra-group panel for balancing within one group of carrier pairs and an inter-group panel for balancing pairs in one group against pairs in a second group of equal size. In the present design, an intra-group panel takes care of 20 pairs (190 combinations) and an inter-group panel of the 400 combinations between two 20-pair groups. To maintain phase equality through a number of panels, it is necessary to install them following a definite pattern. Figure 12 shows a suitable pattern for the 15 panels required for 100 pairs.

In the criss-cross scheme (Fig. 11) the side-to-side combinations, which are those marked 1/2, 3/4, 5/6, etc., appear twice, i.e., along the left and right edges of the panel. Advantage of this is taken by installing balancing coils at both locations. This is done because one side-to-side coil of about 1.3 microhenries may not be large enough in all cases in spite of the fact that the mean side-to-side crosstalk has been reduced 9 db by poling.

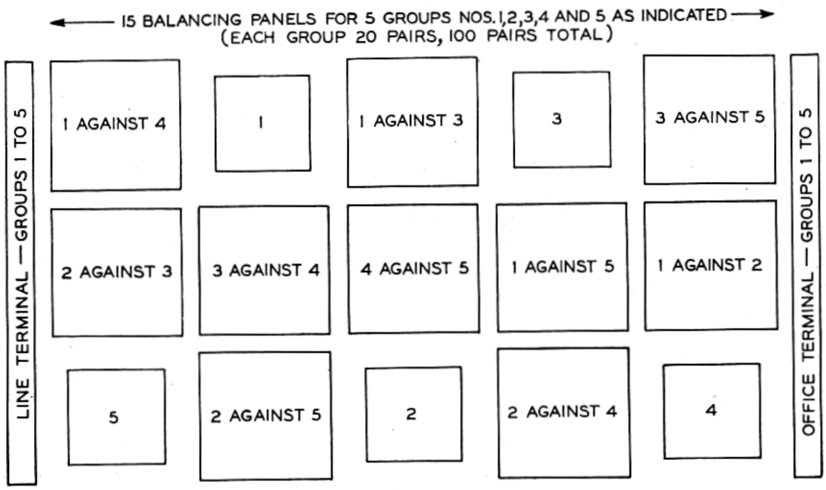

Fig. 12—Allocation of balancing panels designed to maintain phase equalization of coils at all stages. Panels with suitable cross-connections between them are installed in following order.

For first group—Install 1
Add second group—Add 2, and 1 against 2
Add third group—Add 3, 1 against 3, and 2 against 3
Etc.

Balancing Procedure

As stated above, the far-end crosstalk in a repeater section can not be balanced out completely over the frequency range with a single balancing unit. To determine the balanceable as distinct from the non-balanceable crosstalk, involves crosstalk measurements in phase and magnitude at a number of frequencies, using each pair of a two-pair combination as a disturbing circuit in turn. The balanceable crosstalk may then be separated from the non-balanceable crosstalk by computation. Balancing by this method would be impracticable because of the time required. As a practical scheme, it has been shown that balancing at a frequency of about 40 kc. will produce satisfactory results over the type K range even though part of the non-balanceable crosstalk may be neutralized at this frequency. This is theoretically undesirable since the crosstalk reduction at other frequencies is impaired.

To prevent undue interference into operating carrier circuits when balancing, a frequency falling between the transmitted bands must be used. For this reason, the balancing coils are adjusted at a test frequency of 39.85 kc. and a measurement to check the suitability of the adjustment is made at 28.15 kc. Figure 13 shows the crosstalk vs. frequency before and after coil balancing by this method on three repeater sections.

Additional Crosstalk Remedial Measures

Although poling as well as balancing is done to reduce side-to-side crosstalk, this crosstalk is still considerably greater than the pair-to-pair crosstalk. For this reason, side-to-side crosstalk is diluted among

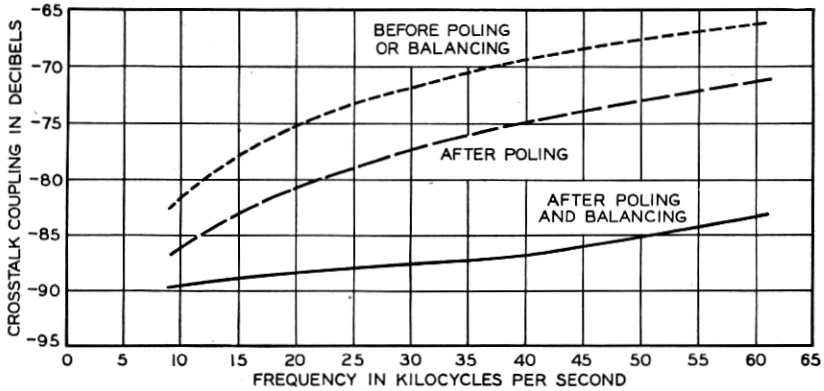

Fig. 13—R.M.S. far-end crosstalk per repeater section from measurements on 3 repeater sections.

the pair-to-pair combinations by a system of quad-splitting at repeater points.

The crosstalk after balancing (Fig. 13) is considerably higher at the upper end of the frequency band than at the lower end. Consequently, if circuits were set up to use the same channel throughout, the crosstalk in the upper-frequency channels would be materially greater than that in the lower-frequency channels. In order that all circuits may be equally satisfactory from the crosstalk standpoint, a system of special channel assignments in successive intervals, say 500 to 1000 miles, can be used. This will tend to equalize both the crosstalk and the noise on all circuits, thus permitting a somewhat cheaper design then if each channel had to meet the crosstalk and noise limits by itself.

Noise

Besides babble, many other sources of noise need to be considered in cable carrier design. Figure 14, which shows the approximate magnitude of several of these if no means are taken to suppress them, indicates the noise at the end of a single 17-mile repeater section when

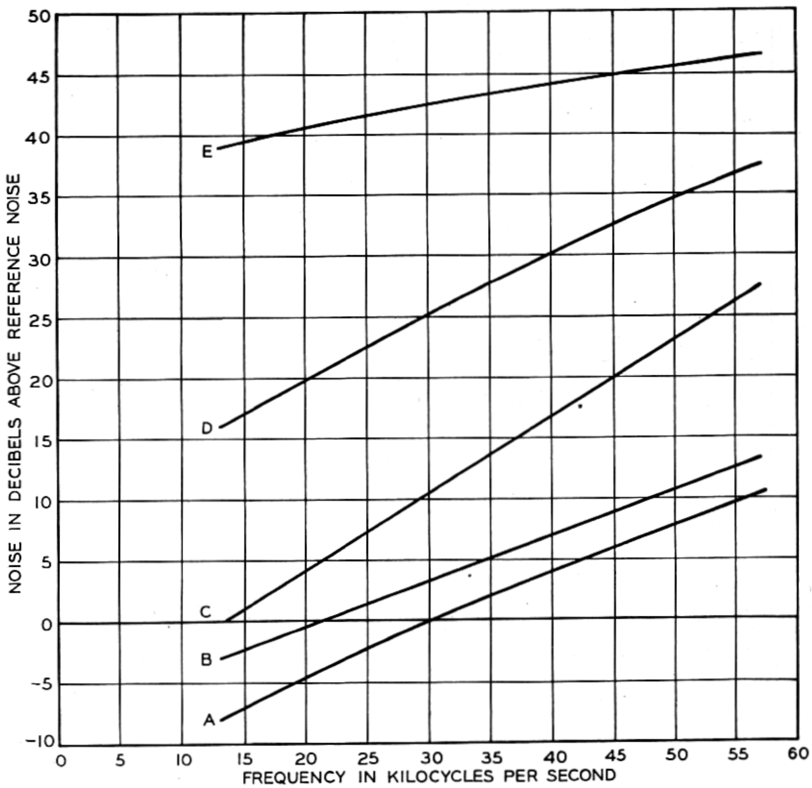

Fig. 14—Noise, prior to suppression measures, per repeater section at output of repeater whose gain equals line loss.

A—Noise from thermal agitation.
B—Thermal agitation plus tube noise.
C—Noise from voice frequency telephone repeater office.
D—Noise from telephone and telegraph repeater office.
E—Noise from heavy static on open-wire tap close to carrier repeater input.

amplified by a repeater whose gain equals the hot-weather line loss. Curve *A* shows the unavoidable lower limit of noise, that produced by thermal agitation of the electrons in the cable conductors and the repeater.[2] This amounts to about 2×10^{-17} watts per telephone

[2] J. B. Johnson, *Phys. Rev.*, **32**, 97 (1928); H. Nyquist, *Phys. Rev.*, **32**, 110 (1928).

channel per repeater section, at the repeater input. If there were no other noise sources, the repeater section length would necessarily be limited by this effect. Curve *B* shows the sum of thermal noise and noise due to the vacuum tubes in the repeaters, which is little in excess of thermal noise alone. The other three curves show noises of considerably higher magnitude which require suppression in order to arrive at an economical carrier system. Curve *E* shows the order of magnitude of noise on carrier circuits due to connecting open-wire pairs directly to non-carrier pairs in the outside cable near the carrier repeater input. The source of the noise is heavy atmospheric static of a magnitude experienced several times during the summer.

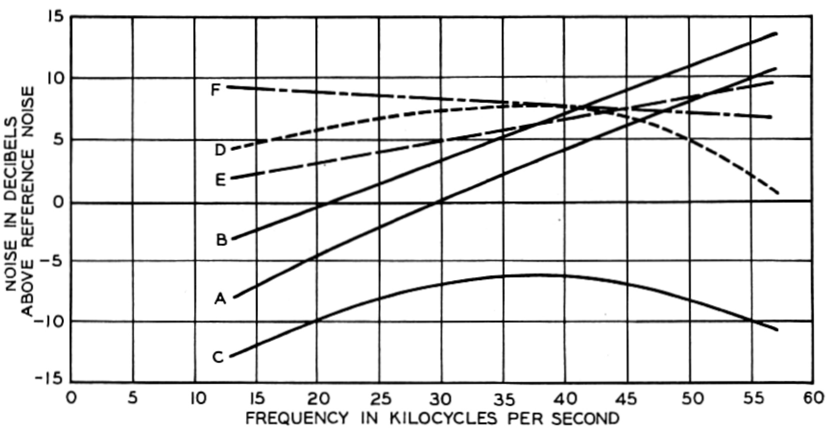

Fig. 15—Noise, subsequent to suppression measures, per repeater section at output of repeater whose gain equals line loss.

A to *E*—Same sources as in Fig. 14.

F—Noise from heavy static induced directly into outside cable.

The other curves show typical magnitudes of noise originating in the existing telegraph and voice frequency telephone plant; this is generated in existing repeater stations and transmitted by the non-carrier pairs to the outside cable where it is induced into the carrier pairs. Curve *D* represents the situation at a combined telephone and telegraph repeater station, and Curve *C*, the situation at a station where there are no telegraph repeaters.

Figure 15 indicates the results after suppression measures have been applied. As shown, at the top frequency, which controls the carrier repeater section length, these sources of noise have been reduced to be well below thermal plus tube noise. It is also shown that the noise due to heavy atmospheric static induced directly into a carrier pair in the outside cable is below thermal plus tube noise at the top frequency.

There are additional types of noise, not shown, whose sources lie within the carrier system: e.g., modulation in amplifiers, inter-system cross-induction, battery noise. While control of such noise is an integral part of the fundamental carrier system design, it is not the purpose of this paper to cover this class of noise.

Conductors Tapping the Carrier Cable

Carrier noise may come from open-wire pairs which connect to conductors in the cable. Its sources may be static; corona on power lines; power line carrier or other carrier frequency voltages on power lines paralleling the open wire; induction from radio telegraph stations; or carrier frequency voltages arising in the office to which the open

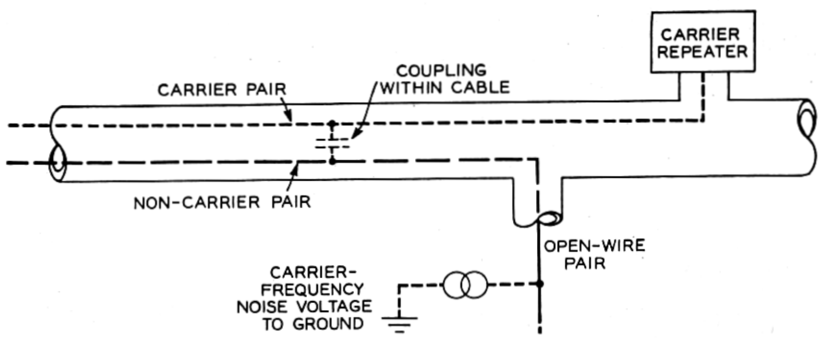

Fig. 16—Schematic of path followed by induction from open-wire taps.

wire is connected, such as voltages generated by d-c. telegraph or telephone signaling systems. The limited experience to date indicates that, in a long cable carrier system, the effect of heavy static will be larger than that of the other sources if telephone and power supply plants are coordinated so as to be satisfactory from voice frequency and low frequency standpoints. Branch cables connected to the carrier cable have a similar but generally smaller effect than that of open-wire taps.

Figure 16 illustrates the path followed by this induction. A voltage to ground impressed on the open-wire pairs passes by secondary induction over to the carrier pairs in the cable, and, on account of the unbalance to ground of these pairs, produces a metallic voltage on these pairs at the repeater input. The effect may be greatly reduced by interposing a filter at the junction of the open wire and the cable.

It is necessary to filter only the longitudinal circuit at an open-wire tap, because: (1) the voltage to ground on the open wire is larger than the metallic circuit voltage, and (2) the coupling between the longitudinal circuit and the disturbed carrier pair is greater than the coupling between metallic circuits.

Figure 17 is a schematic diagram of the longitudinal filter developed for a phantom group. It consists of two longitudinal retardation coils and a set of condensers connected between the line wires and the cable sheath. This filter has relatively high carrier frequency longitudinal impedance to minimize effects of impedance in the ground connection. The major portion of the carrier frequency impedance of the coils is obtained by designing them to have high core loss at these frequencies. The filter has little effect on voice frequency transmission, precaution having been taken to hold the transmission loss, crosstalk and unbalance to ground to low values.

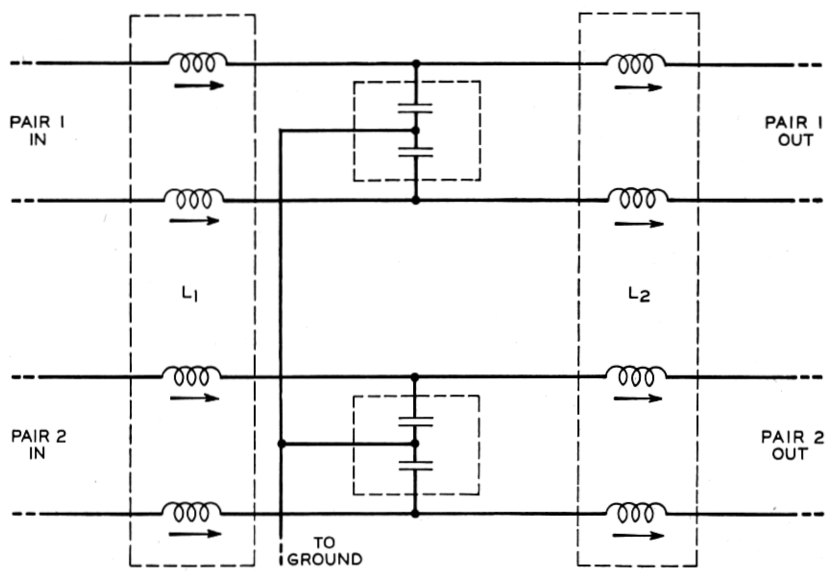

Fig. 17—Schematic of longitudinal filter.

Noise Arising in Existing Repeater Offices

The noise caused by carrier frequency voltages generated in existing repeater offices is due to d-c. telegraph, telephone speech and signaling voltages, power supply, etc. Figure 1 shows the path by which they reach the carrier plant and the means used to suppress them. In this figure, *N* represents a source of carrier frequency voltage in a repeater office, connected to a voice frequency pair which transmits this voltage into the outside cable where it is induced on the carrier pairs. These voltages are reduced by inserting suppression coils in the longitudinal voice frequency paths at the junction between the office and the outside cable connected to carrier inputs.

The design of coils giving the requisite carrier frequency suppression without appreciably affecting voice frequency transmission on the circuits in which they are connected was difficult. One coil is used for each phantom group. Each coil has sixteen windings, four for each line wire. These windings are so paired and disposed about the core

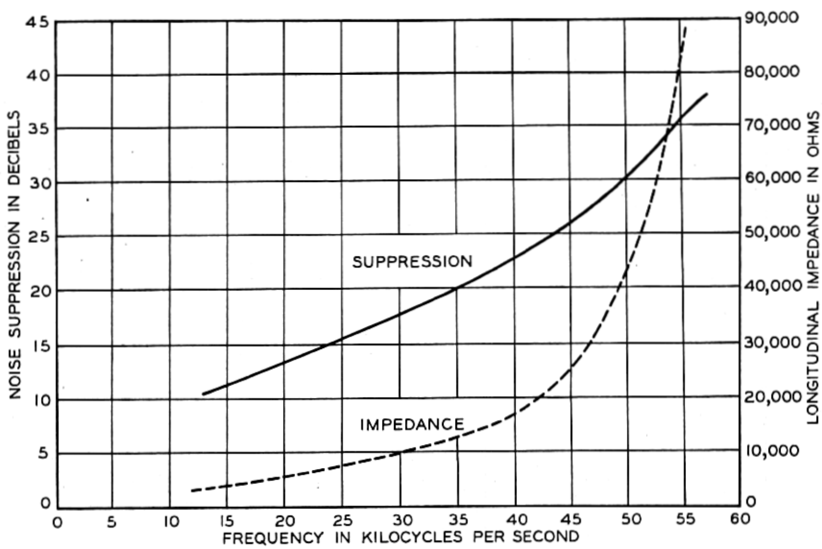

Fig. 18—Longitudinal impedance and suppression of noise suppression coils.

as to make possible very small side-to-side and phantom-to-side crosstalk between line windings. They also permit obtaining very small leakage flux in both the sides and the phantoms; hence the coils introduce very small transmission loss in their voice frequency circuits. The leakage impedance of the coils plus the impedance of the cable stub used to connect them into the circuit is held down so that the effect on repeater singing and echoes in the voice circuits is very small. The coils are so wound that their longitudinal inductance is in antiresonance with their distributed longitudinal capacitance at approximately the top cable carrier frequency, resulting in a large increase in their suppression in this critical frequency range. The longitudinal impedance of one of these coils, and the approximate suppression which a set of them provides, are shown in Fig. 18.

In addition, the carrier circuits are carefully separated, electrically and physically, from existing voice frequency circuits in common repeater stations. To this end the carrier pairs in the outside cable are brought out on the line side of the noise suppression coils into a separate cable connected directly to a sealed terminal. From this terminal they are carried in shielded wire to the units in the carrier office and then to a similar sealed terminal leading to the outside cable in the opposite direction. Filters for filament and plate battery supply are included in the carrier amplifiers and additional filament battery supply filters are provided at the carrier fuse panels.