Telephone Transmission Over Long Cable Circuits

By A. B. CLARK

SYNOPSIS: The application of telephone repeaters has made it possible to use small gauge cable circuits to handle long distance telephone service over distances up to and exceeding 1,000 miles. A general picture of the long toll cable system which is being projected for use in the northeastern section of the United States was presented recently by Mr. Pilliod and published in the July number of the Technical Journal.

Many of the circuits in these toll cables are so long electrically that a number of effects, which are comparatively unimportant in ordinary telephone circuits, become of large and sometimes controlling importance. For example, the time required for voice energy to traverse the circuits becomes very appreciable so that reflections of the energy may produce "echo" effects very similar to echoes of sound. The behavior of the circuits under transient impulses, even when two-way operation is not involved so that "echoes" are not experienced, is very important. In order to keep within proper limits of variation of efficiency with frequency over the telephone range special corrective measures are necessary. Owing to the small sizes of the conductors, the attenuations in the longer circuits are very large. Special methods are, therefore, required to maintain the necessary stability of the transmission, including automatic means for adjustment of the repeater gains to compensate for changes in the resistance of the conductors caused by temperature changes.

THIS paper aims to present an idea of what is involved in the transmission of voice currents over long toll cable circuits. Because of the breadth of the subject covered, no attempt has been made to make the discussions of the various items complete, or to include many of the results of the experimental and theoretical work which contributed to a solution of the problems and which has involved the cooperative efforts of a large number of engineers and investigators. This paper should be considered merely as an introduction to the subject. It is hoped that subsequent papers will be presented dealing with these matters in more detail.

For the benefit of those who are not intimately in touch with telephone transmission work, the different types of circuits used in toll cables are first briefly reviewed. The important characteristics of the loading systems are then presented. Following this, various important effects encountered in long cable circuits are discussed and their reactions on the design of cable systems indicated.

In view of the discussion on telephone repeaters given in the Gherardi-Jewett paper,[1] which was presented before this Institute on October 1, 1919, it will be assumed that the reader of the present paper is familiar with the general features possessed by the various types of such devices and, accordingly, no descriptions of them are given, their overall performance only being of interest in the present connection.

[1] Transactions of A. I. E. E., Vol. XXXVIII Part 2—Page 1287.

I. DIFFERENT TYPES OF CIRCUITS

The different types of circuits used in toll cables are illustrated in diagrammatic form in Figure 1. Circuit "b" is a two-wire telephone circuit employing a 21-type telephone repeater. This type of circuit is employed only for handling connections on which but one telephone repeater is involved. Circuit "c" is a typical two-wire circuit on which the familiar 22-type telephone repeaters are operated. Circuit "d" is of the four-wire type which employs two transmission paths, one for each direction. The function of the pilot wire circuits, "a," will be taken up later.

With the exception of circuit "b", which possesses the limitation that it cannot advantageously be connected to another circuit containing telephone repeaters, the circuits shown in the figure may be connected when required to circuits of the same or other types, such as open-wire circuits, to build up various telephone connections. In general, circuits such as "c", employing 22-type repeaters, are used for handling connections of moderate lengths, while circuits such as "d", of the four-wire type, are employed for the longer connections where the transmission requirements are more severe.

In addition to employing the cable conductors for furnishing telephone service, these may also be arranged to furnish D.C. telegraph service. Apparatus for compositing the circuits so as to permit this superposition of the D.C. telegraph is indicated on the drawing. In general, the method of compositing the small gauge cable circuits is the same as that employed for compositing open-wire lines. The telegraph circuits in cable, however, operate with a metallic instead of a grounded return and employ much weaker currents than those common on open wires. Telegraph currents employed in the cables are comparable in magnitude with the voice currents.

The two-wire circuits in toll cables employ conductors of No. 19 or No. 16 American wire gauge, while for the four-wire circuits, No. 19 gauge conductors are usually employed. (No. 19 gauge weighs 20½ pounds per wire mile or 5.8 kilograms per kilometer. No. 16 gauge weighs twice as much).

II. LOADING CHARACTERISTICS

Two weights of loading are usually employed. These are commonly known as "medium heavy loading" and "extra light loading" and in this paper they will be referred to for brevity as "M.H.L." and "X.L.L." respectively. The medium heavy loading employs coils having an inductance of about 0.175 henry in the side circuits,

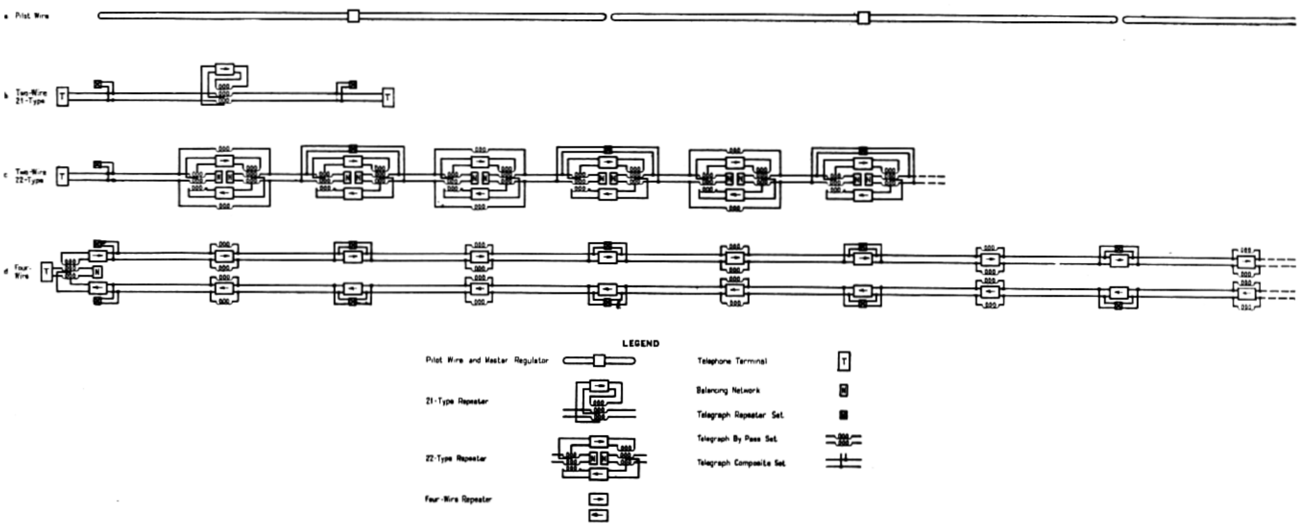


Fig. 1—Different types of cable circuits.

spaced 6,000 feet apart (approximately 1.8 kilometers); the extra light loading employs coils having an inductance of about 0.044 henry for the side circuits with the same spacing. The capacity per loading section for the side circuits is approximately 0.074 mf.

The medium heavy loaded side circuits have a characteristic impedance of about 1600 ohms, and a cutoff frequency of about 2800 cycles. The extra light loaded side circuits have an impedance of about 800 ohms and a cutoff frequency of about 5600 cycles.

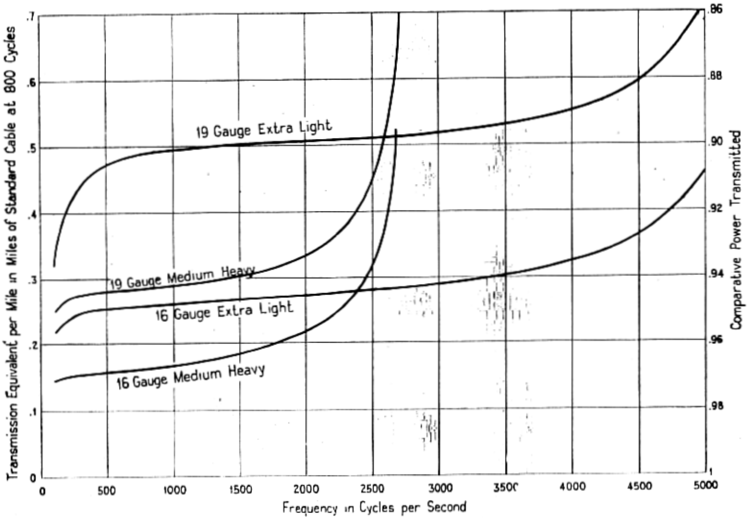


Fig. 2—Attenuation-frequency characteristics of loaded cable side circuits.

Figure 2 shows the attenuation-frequency characteristics of No. 19 and No. 16 gauge side circuits with the two types of loading. It will be observed that the M.H.L. circuits have lower attenuation for frequencies below about 2500 cycles, as should be expected from the fact that the inductance per mile introduced by the loading coils is greater. However, the attenuation is more nearly equal at different frequencies in the case of the X.L.L. circuits, this being particularly true at the higher voice frequencies.

Another important characteristic of loaded circuits when repeaters are involved is their velocity of propagation. Since the inductance per mile of X.L.L. circuits is only ¼ of that for M.H.L. circuits, the velocity of propagation is twice as great for the X.L.L. circuits as indicated by the well-known approximate formula—

$$V = (L\,C)^{-1/2}$$

Where V is the velocity in unit lengths per second, L is the inductance in henries per unit length and C is the capacity in farads per unit length, the unit of length for expressing velocity, inductance and capacity being the same.

The X.L.L. type of loading is best for the longer circuits, because of the more nearly equal attenuation of currents of different frequencies, its higher velocity of propagation which permits more efficient operation of telephone repeaters, and also its comparative freedom from transient effects, as will be explained in more detail later. For the shorter circuits where these effects are not so important, the M.H.L. type is satisfactory electrically and is therefore employed since fewer repeaters are required owing to the lower attenuation.

III. "Echoes"

As is well known, whenever points of discontinuity or unbalance occur in a telephone circuit, reflections of electrical energy take place. If the circuit is long so that the time for transmission is appreciable and if also the losses are not so great as to cause the reflected energy to become inappreciably small before it reaches the ear of a listener, echo effects will be experienced. While, in general, reflections take place in any telephone circuit actual echoes are never appreciable unless telephone repeaters are employed. In the case of circuits with repeaters, the electrical length is usually great enough so that an appreciable length of time is required for the voice currents to travel to some discontinuity and back again. Furthermore, the repeater gains keep the reflected voice currents large.

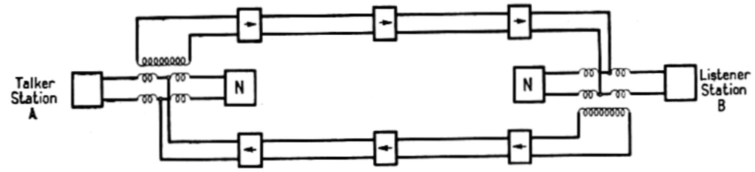
It should be understood that the echo effects which are experienced in long repeatered circuits are due to the same unbalances, which, on shorter circuits, bring in trouble due to "singing", or distortion of the voice waves due to "near-singing". On electrically long circuits, due to the comparatively great time lags involved, the echo effects become of controlling importance. Consequently, it is, in general, necessary on such circuits to work the repeaters at gains well below those at which "singing" or distortion due to "near-singing" is experienced.

The echo effects which occur in four-wire circuits will first be discussed, since the effects are simpler in this case than they are in the case of a two-wire circuit.

Figure 3-a shows a four-wire circuit in diagrammatic form, while Figure 3-b shows the echoes which are caused by the unbalances at the terminals. When someone at terminal A talks to a person at

terminal B, the heavy line in Figure 3-b shows the direct transmission, which takes place over the top pair of wires in Figure 3-a. When this current reaches the distant terminal, part of it goes to the listener while another part, due to the imperfections of balance between the line and network at that terminal, travels back through the pair of wires at the bottom of Figure 3-a toward terminal A. The talker at terminal A will hear this current as an echo if the four-wire circuit is long enough so that the time lag is appreciable. This first echo heard by the talker divides at terminal A in the same way as did the direct transmission at terminal B, part of it taking the upper path of figure 3-a back toward the listener. The listener will, therefore, first receive the direct tansmission and then a little later an echo. This process is repeated producing successive echoes which are received at both terminals A and B as indicated.

a-Four Wire Circuit



b - Echo Paths

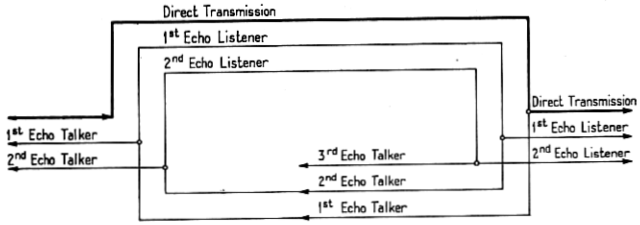


Fig. 3—Echo paths in four-wire circuit.

A four-wire circuit 1000 miles (1600 kilometers) long has been set up in which the balances at the two ends were deliberately made poor so as to exaggerate the effects. More than a dozen successive echoes could be heard before they became inaudible. Since for each echo the voice energy traveled 2000 miles (3200 kilometers) this energy must have travelled the distance around the world before becoming inaudible.

In order that a circuit will be satisfactory for regular telephone use, the echoes must be kept small as compared to the direct transmission. Evidently if the first echoes are small as compared to the direct transmission, the later echoes will be much smaller in magnitude. For example, if the power in the first echo, heard by the listener, is 1-10 as great as the directly transmitted power, the second echo will have only 1-100 as much power, the third echo 1-1000 etc.

The velocity of an X.L.L. circuit is approximately 20,000 miles (32,000 kilometers) per second, while the velocity with M.H.L. is only 10,000 miles (16,000 kilometers) per second. It is thus seen that the time required for voice energy to travel from one end to the other of an X.L.L. circuit 1,000 miles (1600 kilometers) long is 0.05 second. An echo traveling from one end of the circuit to the other and back again would, therefore, arrive 0.1 second behind the impulse which started the echo. With M.H.L. circuits these times are of course doubled.

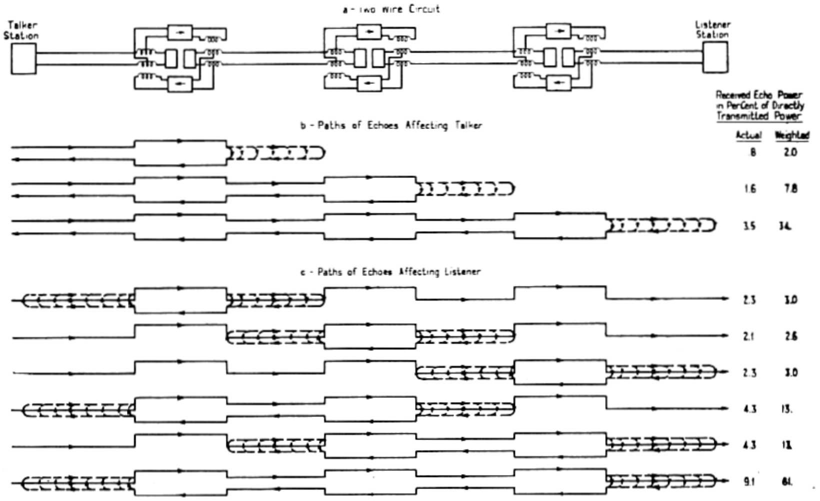


Fig. 4—Echo paths in two-wire repeatered circuit.

Figure 4 illustrates the condition existing in a two-wire circuit. For simplicity, the first echoes only are shown, the later echoes being less important owing to their comparative weakness as explained above. In such a circuit reflections occur not only at the terminals, but at a number of intermediate points in the circuit, the condition of balance between the networks associated with the telephone repeaters and the corresponding lines being necessarily imperfect. This imperfection of balance is due in part to lack of perfect balance of the apparatus closely associated with the repeater, and in part to the small irregularities which exist in the make-up of any practical loaded line. A further cause is the reflection at the adjacent repeaters, due to the difference between the repeater impedance and the line impedance.

It will be noted that three sets of echoes are shown which affect the "talker". In addition to these which involve one or more repeaters, a comparatively small amount of power is reflected back to the "talker" from the various irregularities between the "talker" station and the nearest repeater. These reflections have not been indicated since their effects are of negligible importance. Six sets of echoes affect the "listener". Both for the echoes affecting the "talker" and the "listener", the dotted lines indicate reflections from a number of different points where irregularities exist as explained above.

In circuits containing a larger number of repeaters the numbers of sets of echoes affecting the talker and listener are, of course, greater. The number of sets of first echoes affecting the talker is equal to the number of repeaters. The number affecting the listener is equal to $\frac{N(N+1)}{2}$ where N is the number of repeaters.

It is, of course, obvious, that, for either four-wire or two-wire circuits, if the circulating energies are large, they will have an adverse effect on the ability of two people to carry on a conversation over a telephone circuit. Not only will the transmission received by the listener be adversely affected, but the talker will be considerably distracted, particularly when the time of the transmission over the circuit is so long that he hears a distinct echo of his words.

Experiments have shown that the effects of the echoes both on the listener and talker become more serious as their time lag is increased. This means that as telephone circuits are made longer it is necessary either to improve balances or to design the telephone circuits so that the velocity of propagation will be higher. This necessity for making the velocity of propagation high on long circuits was one of the principal reasons which led to the selection of extra light loading for the longer circuits.

Figure 5 shows very approximately how the effects of the echoes vary with the length of time by which they are delayed. One curve is given for the effect on the "talker", another for the effect on the "listener". Both curves indicate, for various time lags, the comparative magnitude of echoes which are small enough to be inappreciable when ordinary telephone conversations are carried on. The curve applying to the "listener" is referred to the direct power which he receives, while the curve for the "talker" is referred to the power which he puts into the circuit.

In Figure 4 showing the condition existing in a two-wire circuit, the comparative magnitudes of the power in each echo are indicated, a typical condition of the lines being assumed. For the listener the echo power is expressed as a percentage of the directly transmitted power which he receives. In the case of the talker, it is expressed as a percentage of the power which he puts into the circuit. In addition to the comparative amounts of power in each echo, "weighted" magnitudes are indicated. The "weighted" figures take account of the fact that the effects of a given amount of echo become more serious as the time lag is increased as indicated by the curves in Figure 5.

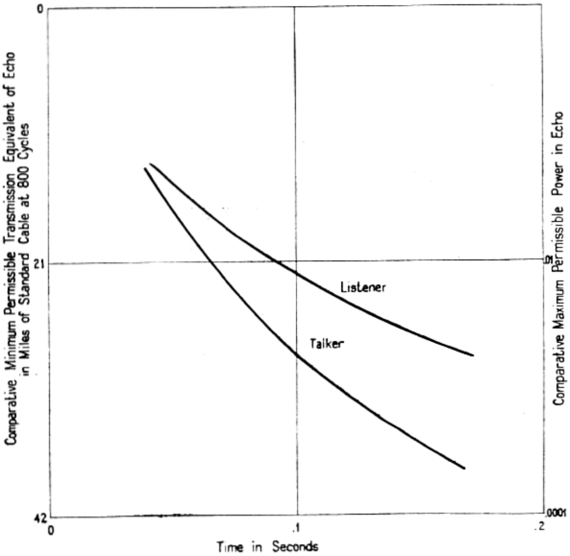


Fig. 5—Effect of echoes on talker and listener.

Referring to Figure 4, it will be noted that the "weighted" magnitudes of the power in the echoes are largest for the long paths. In general, this condition exists in the case of the majority of long two-wire repeatered circuits in cable.

In order to compare the behavior of a four-wire circuit with a two-wire circuit, consider again Figures 3 and 4. It will be observed that in Figure 4, showing the two-wire circuit, there is one echo received by the talker which travels from one end of the circuit to the other. Referring to Figure 3 showing a four-wire circuit, it will be seen that this echo corresponds to the one labelled "1st echo talker". Similarly for the echoes affecting the listener, the echo whose path is longest in the two-wire circuit corresponds to a similar echo in the four-wire circuit. Since many additional echo paths are present in the two-wire circuit, it is evident that, other things being equal, the overall transmission result obtainable from the two-wire circuit cannot be made as good as that obtainable from the four-wire circuit.

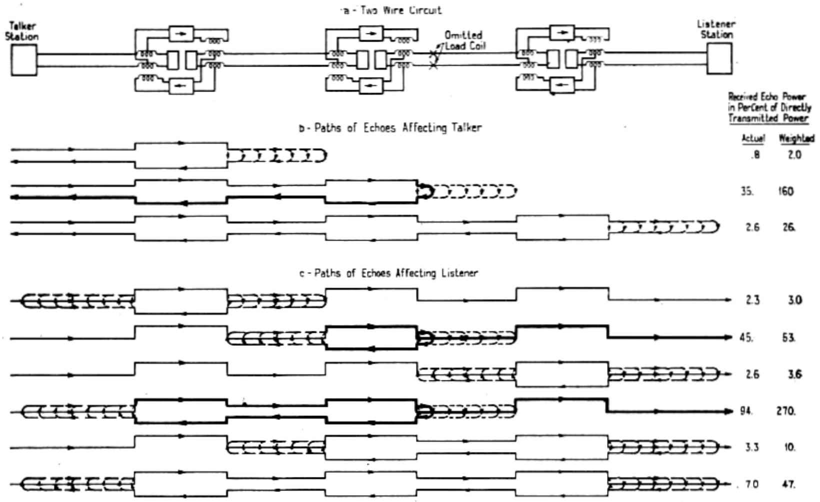


Fig. 6—Echo paths in two-wire repeatered circuit with omitted loading coil.

In a two-wire circuit it is, of course, obvious that any defect in the lines which will cause a large irregularity will result in a considerable impairment of the circuit. Figure 6 shows the effect of omitting a loading coil at an intermediate point in a circuit, the conditions in this circuit being assumed to be the same as those in Figure 4 with the exception of the omitted loading coil. The omitted loading coil introduces a large impedance irregularity which causes certain of the echoes to be made much greater in comparative magnitude as indicated. In order to reduce the echoes in the circuit with the omitted loading coil sufficiently to make the circuit satisfactory for telephone use, it is necessary to reduce the repeater gains. In this particular case it is necessary to lower the total gain about 4 miles, which increases the overall transmission equivalent of the circuit from about 10 miles for the normal condition to about 14 miles for the condition with the omitted loading coil.

Before leaving the subject of "echoes" it is believed that it will be of interest to point out some of the important characteristics of two-way repeatered circuits which result from these effects.

1. The minimum permissible net equivalent (total loss minus total repeater gain in one direction) of a four-wire circuit of a given length depends only on the velocity of propagation and the balance conditions at the terminals of the circuit. When conditions are such that the balance conditions cannot be improved, increasing the velocity of propagation will enable a lower net equivalent to be obtained.

2. In the case of a two-wire circuit with reasonably smooth lines, the exact location of the repeaters and the gains at which individual repeaters are worked have little effect on the overall result so far as echo effects are concerned. This follows from the fact that the echo paths from end to end of such a circuit are usually of more importance than the shorter echo paths. Evidently, moving the individual repeaters about or altering their gains has no effect on the longest paths, provided the total gain in each direction is kept constant.

3. In the case of a two-wire circuit of a given length, the velocity of propagation and smoothness of the lines are of most importance in limiting the possible net equivalent, the line attenuation being of secondary importance.

   For example, in the case of the transcontinental (New York-San Francisco) open-wire line, the original circuit was loaded. (Although this paper deals particularly with repeaters on cable circuits this example was selected because it so well illustrates this point.) The velocity of propagation was such that voice currents required about 0.07 second to travel from one end of the circuit to the other. The total line equivalent was equal to about 56 miles of standard cable. By applying repeaters to this circuit it was possible to obtain a working net equivalent of about 21 miles.

   The unloading of the circuit increased the velocity so that the time of transmission was reduced to 0.02 second, about 0.3 of the time required when the circuit was loaded. The attenuation was increased so that the total line equivalent without repeaters was equal to about 120 miles of standard cable, a little more than twice the equivalent of the loaded circuit. By applying repeaters of an improved type to this circuit so as to keep the quality good in spite of the increased attenuation and

> correspondingly increased gain required, it was possible to obtain a working equivalent of only 12 miles of standard cable as compared to the original figure of 21 miles. This means that with the same amount of speech power applied at one end, the power received over the non-loaded circuit is 7 times as large as that formerly received over the loaded circuit.[2]

The example of the transcontinental line, above, may well bring up the question as to why it is that cable circuits are loaded. This is done for two reasons: In the first place, it is in general cheaper to load cables than it is to make up the increased attenuation by means of more repeaters. In the second place the loading lessens the amount of distortion introduced by the cable circuits. In the case of open wire circuits, their series inductance is sufficient to keep the distortion small.

IV. ATTENUATIONS AND CORRESPONDING AMPLIFICATIONS—POWER LEVELS

Owing to the fact that the weight of loading applied to the longest cable circuits is very light, the attenuation of such circuits is very great. A four-wire X.L.L. 19 gauge circuit 1,000 miles long has the enormous line equivalent of 500 miles of standard cable. The total power amplification applied to this circuit by the repeaters exceeds 10^{47}. This amount of amplification is more than enough to talk half way around the world at the equator using non-loaded No. 8 Birmingham Wire Gauge open-wire commonly employed for handling very long distance business (No. 8 B.W.G. copper weighs 435 pounds per wire mile, or 120 kilograms per kilometer).

In order to obtain an idea of how enormous this amplification is, assume that no repeaters were employed and an attempt were made to apply enough power at one end of the circuit to enable the normal amount of speech power to be received at the distant end. The power applied at the sending end would then have to be about 50 quadrillion times as great as the total power which it is estimated is radiated by the sun.

While the total amount of power amplification is very great, the amount of amplification put in at any one point is, of course, limited. The maximum amount of power at a repeater point is limited partly by the capacity of the vacuum tubes and partly by the power carrying capacity of the telephone circuit, including the loading coils. (By power carrying capacity is here meant the ability to carry voice waves

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[2] A material improvement in the telephone quality was also effected by the unloading of the circuit.

without serious distortion.) It is also necessary to limit this power to avoid serious crosstalk into other circuits.

In addition to these limitations on the maximum power, it is necessary to insure that the power at any point in a circuit does not become too small. Otherwise, the normal voice power will not be sufficiently large as compared to the power of crosstalk from other circuits. It is, furthermore, evident that the ratio of power from extraneous sources, such as paralleling telegraph circuits and power supply circuits, to the voice power should be as small as practicable in order to keep the circuits free from noise.

Figure 7 will give an idea of how the telephone power attenuates and is amplified in a long circuit. The circuit shown is similar to those which it is proposed to employ between New York and Chicago, *i. e.*, it is a four-wire X.L.L. 19 gauge circuit largely in aerial cable, equipped with automatic means for compensating for the changes in attenuation caused by the effects of varying temperatures on the resistance of the conductors. (These automatic devices are described in a later section of this paper.) For simplicity, the power levels for transmission in one direction only are shown. The solid lines show the power levels when the temperature is a maximum so that the attenuations are greatest, while the dotted lines show the levels when the temperature is a minimum and the losses are, therefore, also a minimum. The shaded areas between the lines represent the changes which take place during the course of a year.

When the requirement is introduced that transmission must take place in both directions it is found that at the points in the circuits going in one direction where the power is a maximum, the power going in the opposite direction in other circuits is a minimum. This represents a very bad condition for crosstalk from one four-wire circuit into another. In order to overcome this the conductors carrying strong voice power are kept electrically separated or shielded from those carrying weak power as indicated schematically in Figure 8. The conductors which carry strong voice power are shown heavy, while those carrying weak power are shown light. In the cable proper the separation is effected by grouping the conductors in two bunches, one for transmission in one direction, the other for transmission in the opposite direction, taking care that these two bunches of conductors are separated electrically as far as possible. In the loading coil pots the coils employed on the circuits for transmission in the two directions are similarly kept separated. In the offices the separation is effected by arranging the repeaters and other apparatus as shown in the figure. It will be observed that no special separation

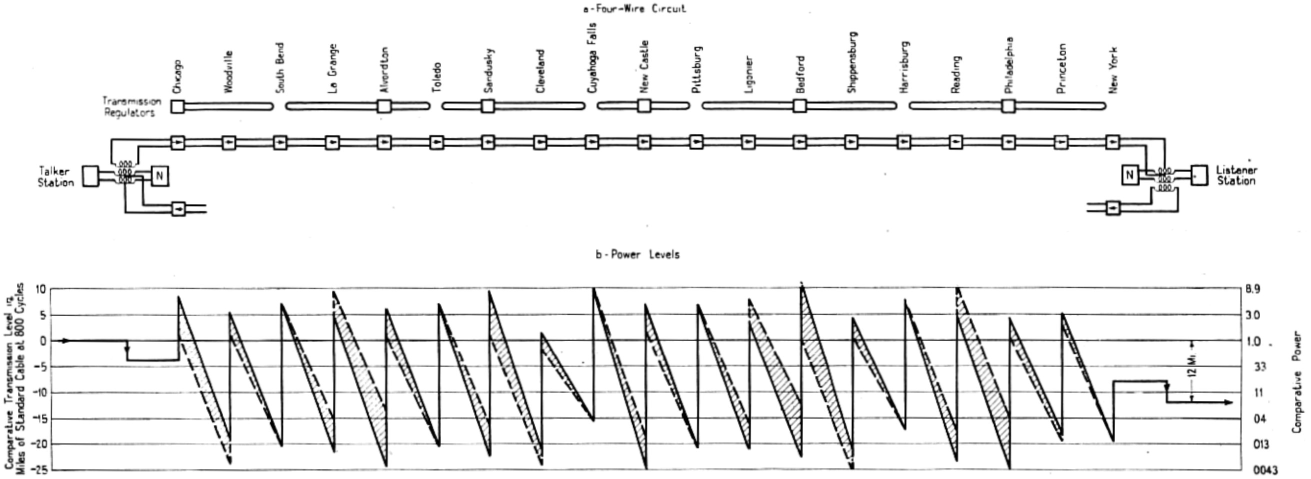

Fig. 7—Power levels in New York-Chicago extra light loaded four-wire circuit.

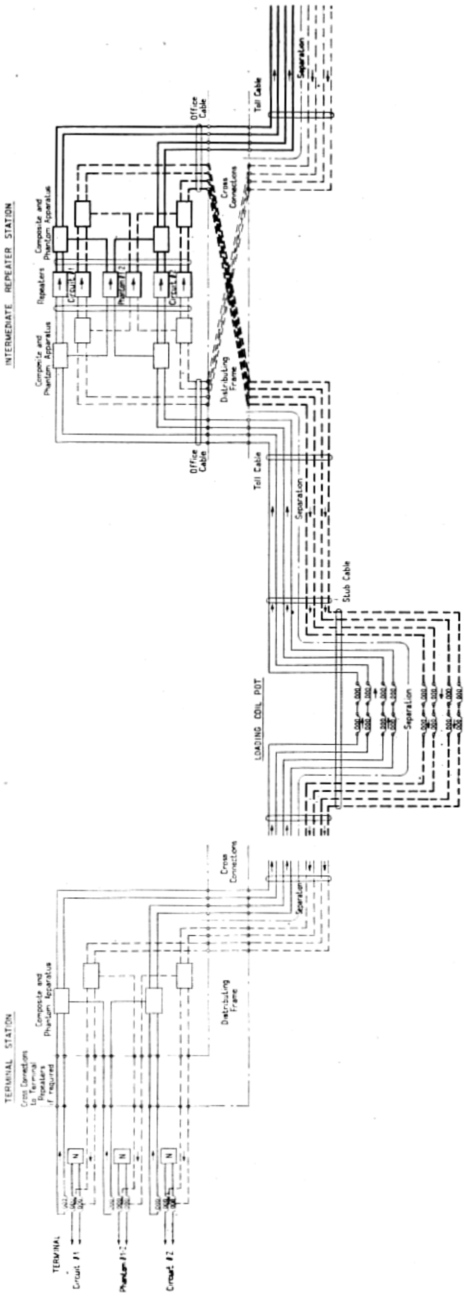

Fig. 8—Four-wire system—Segregation method to reduce cross-talk.

is shown between the repeaters transmitting in the two directions, since to keep the conductors carrying weak power separated from those carrying strong power, it is merely necessary to keep the apparatus and cabling connected to the inputs of the repeaters separated from the apparatus and the cabling connected to the repeater outputs.

V. Steady State Distortion

The possible sources of distortion may be divided broadly into (1) repeaters and auxiliary apparatus and (2) the lines.

With reference to the distortion introduced by the repeaters, the vacuum tube is fortunately very nearly perfect, at least in so far as concerns practical telephony. At one time, for purposes of test, a circuit was set up containing 32 vacuum tubes in tandem. On this circuit the distortion was so small that when listening to ordinary conversation it was difficult to detect any difference in the quality of transmission before and after traversing the 32 vacuum tubes.

It is beyond the limits of this paper to enter into the problems of design which were encountered in the development of the repeater circuits. For the present purpose of considering the overall performance of repeatered circuits in cable no serious error will be made if it is assumed that the complete repeater circuits meet the requirements for an ideal repeater as set up in the Gherardi-Jewett paper.

Considering next the lines, it is necessary to make the loading very regular so that balance difficulties will not cause an undue amount of trouble on two-wire circuits. Regularity of the loading is also essential in order to avoid irregular transmission of different frequencies. In order to secure this regularity of loading, it is necessary that the spacing between loading points be made very uniform and that the cable be so manufactured that the electrostatic capacity of its circuits be held within close limits. The loading coils themselves must be closely alike in their electrical properties and furthermore, the coils must be stable, *i. e.* these electrical properties must not change appreciably due to the passage of voice currents or other currents required for cable operation through them.

Next, it is necessary to design the repeaters and associated apparatus used on the longer circuits, particularly the four-wire circuits, so as to put in different amounts of gain at different frequencies, thereby making the overall transmission at different frequencies approximately constant in spite of the fact that the loss introduced by the cable circuits at different frequencies is not constant. Figure 9 shows the overall or net transmission equivalent plotted against frequency for an X.L.L. four-wire circuit 1080 miles long (1750 kilometers) which was set up for purposes of test. The heavy line in this figure shows the overall result which was actually obtained with repeaters and associated apparatus designed to equalize the transmission, while the dotted line shows what the characteristic would have been had the repeaters introduced exactly the same amount of gain at all frequencies.

VI. Transients

In comparatively short telephone circuits, good quality will usually be assured if the transmission, as measured at different single frequencies within the voice range, is kept approximately constant. For electrically long circuits, however, this is not sufficient. Not only must the "echo" effects be kept within proper limits, but consideration must be given to the fact that when electrical impulses are applied to such circuits, peculiar transient phenomena are experienced. These transient phenomena occur in equal degree in two-way circuits and in circuits arranged to transmit in one direction only, that is, they are not related to "echo" effects.

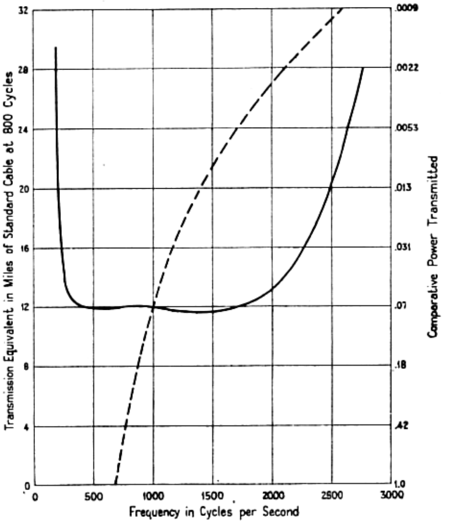

Fig. 9—Transmission frequency characteristic of long extra light loaded four-wire circuit.

In order to give an idea of the nature of some of the transient effects, some oscillograms are shown in Figures 10, 11, 12 and 13. Figure 10 shows an 1800-cycle current before and after traversing a cable circuit of an earlier type 1050 miles (1700 kilometers) long. This particular circuit was No. 13 A.W.G. weighing 82 pounds per wire mile

(23 kilograms per kilometer) loaded with inductance coils of 0.2 henry spaced 1.4 miles (2.25 kilometers) apart and contained 6 one-way repeaters. It will be noted that the first sign of the arrival of the received current occurs about 0.1 second after the wave is put on at the sending end. This time checks with the formula for velocity given above. The time required after arrival of the first impulse (point "a") until the wave builds up to a practically steady-state condition at point "b" is about 0.055 second. The steady condition is interrupted at point "c" by the arrival of the break transient, the time interval between points "b" and "c", representing the period when the wave is in the steady-state, being only 0.01 second. The wave required about 0.055 second to die out—interval between points "c" and "d".

It is interesting to note the behavior of the current during the building-up and dying-out intervals. During the building-up process the frequency of the received current increases from a very low value at point "a" until at point "b" it becomes the same as that of the source. The magnitude of the received current also increases until at point "b" it reaches a value corresponding to the steady-state transmission equivalent of the line. The interval "a-b" is determined solely by the structure of the line and has nothing to do with the time during which the current is supplied at the sending end.

The dying-out process can be considered to be caused by the application at the time of break of a second current equal in value to the current originally applied but opposite in phase, so that the sum of the two currents will be zero. Hence, it is to be expected that the received current will disappear by adding to the steady-state a transient similar to the building-up transient in the interval "a-b". That this is true is indicated by the behavior during the interval "c-d". At first the low frequency current of the break transient produces a displacement of the axis of the steady current. As the frequency approaches a steady value a beating effect becomes noticeable which grows smaller until complete opposition of phase obtains and the received current disappears.

Figure 10 clearly indicates that a pulse of voice current having a frequency in the neighborhood of 1800 cycles, even though received in proper volume if steadily applied, would be badly distorted.

When carrying on a conversation over such a circuit as this, distortion of the voice waves makes understanding difficult while peculiar metallic ringing sounds are very noticeable.

Next consider a circuit of the same character with half the length. The effect of a circuit of this length on an 1800-cycle wave is shown in the oscillogram of Figure 11. It will be observed that the propagation time has been cut in half while the lengths of time for the received wave to build up and die out have also each been cut in two. This checks with theoretical work, indicating that the severity of this type of transient effect is directly proportional to the length of the circuit. This fact that the transient effect is proportional to the length of the circuit furnishes the reason why a short circuit may give tolerably good results, while a long circuit gives poor results.

Figure 12 is of interest as indicating what takes place when we apply a current at the sending end of the circuit whose frequency is so high that no appreciable amount of the steady current will pass through the circuit. In this case only transient oscillations appear at the receiving end of the circuit. This particular circuit was of the same type as the above, although it was only 350 miles long (570 kilometers).

A large number of oscillograms of this sort have been taken in connection with the study of these transient effects. From these and theoretical considerations[3] it has been proved that the effects in a given circuit are much worse at high frequencies than at low frequencies, the severity of the effects, within certain limits, being a function of the ratio of the frequency being transmitted to the frequency of cutoff of the loaded circuit. The gauge of the circuit has practically no effect.

Since in order to give good quality it is necessary to transmit fairly well all frequencies up to at least 2000 cycles, it is obvious that on long circuits in order to keep the transient effects small, the frequency of cutoff must be kept high. In order to do this, it is necessary either to make the loading coils of very low inductance or to space them very close together. This is another one of the reasons why extra light loading was adopted for the long cable circuits. (It will be remembered that the inductance of the side circuit loading coils is only 0.044 henry and the spacing 6000 feet).

The effect of lighter loading on the transient behavior of telephone currents, is shown in Figure 13, which shows a 2000-cycle wave transmitted over an X.L.L. circuit about 1050 miles (1700 kilometers) long. This circuit contained 23 one-way repeaters. It will be observed that both the building-up and dying-out transient periods are very much reduced, which means that all pulses of telephone currents up to at least 2000 cycles will pass through such a circuit with very little distortion.

[3] John R. Carson—"Theory of the Transient Oscillations of Electrical Networks and Transmission Systems". Transactions of A. I. E. E. Vol. XXXVIII, page 407.

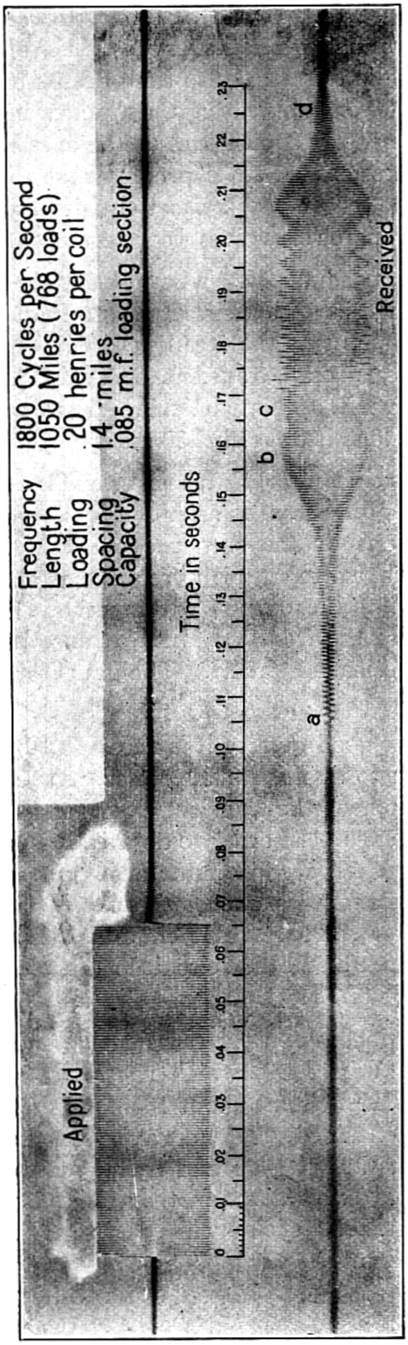

Fig. 10—Transients in 13-gauge medium heavy loaded cable.

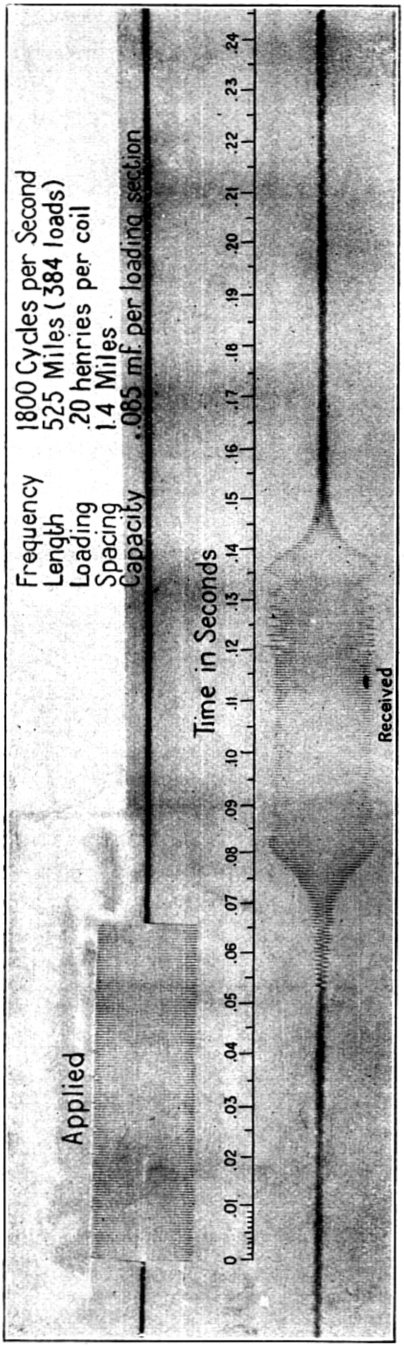

Fig. 11—Transients in 13-gauge medium heavy loaded cable.

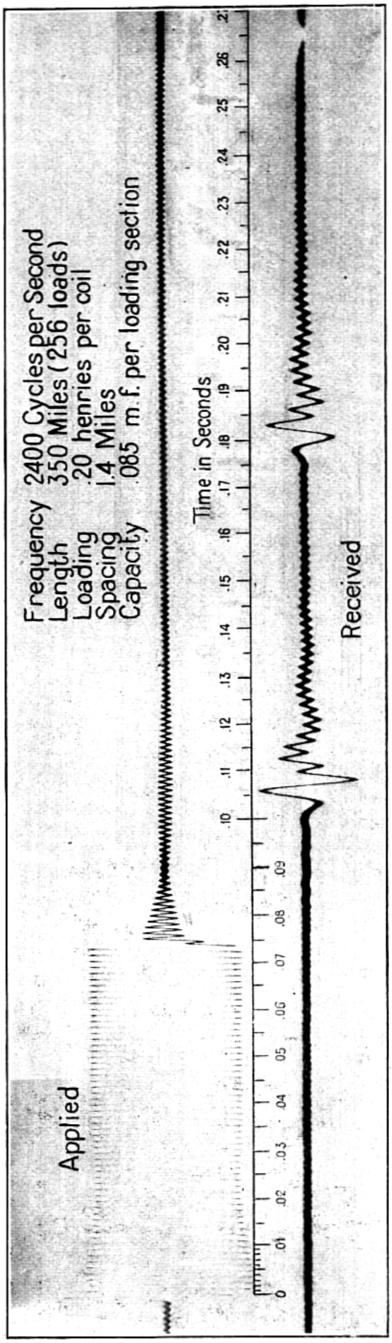

Fig. 12—Transients in 13-gauge medium heavy loaded cable.

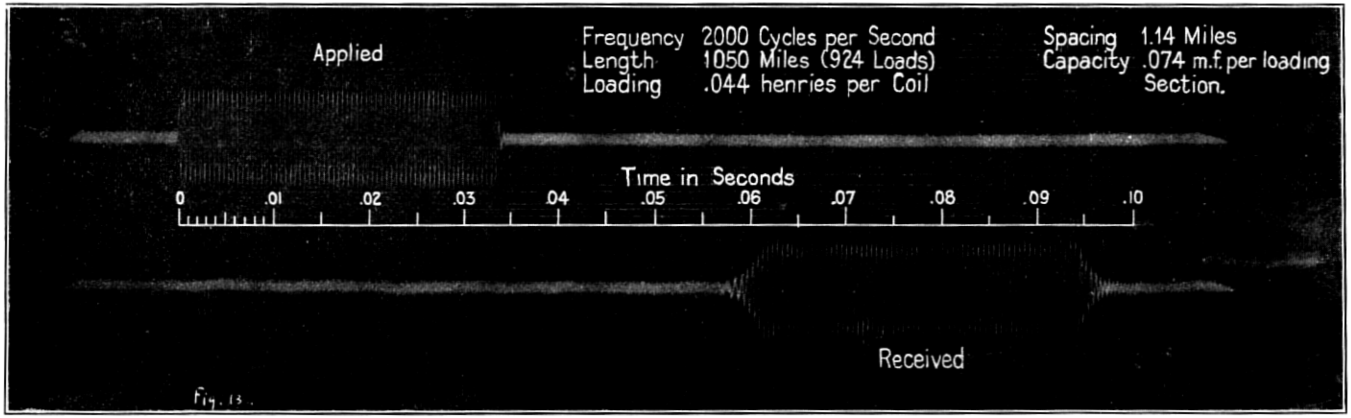

Fig. 13—Transients in 19-gauge extra light loaded cable.

VII. STABILITY

As has been pointed out, the magnitude of the line transmission loss in a repeatered circuit is of comparatively small importance in determining its possible transmission equivalent, whether the circuit be worked on a four-wire or two-wire basis. However, it is of extreme importance to be sure that the repeater gains are kept adjusted so as to compensate exactly for a large part of the transmission loss in the circuit, so that the difference between the total loss in the circuit and the total gain, which represents the net equivalent of the circuit, will be kept constant.

On certain of the long circuits this difference is very small as compared to the quantities which are subtracted. For example, in the case of a 1000-mile four-wire circuit using X.L.L. 19-gauge conductors, the total line transmission loss is about 500 miles. Not counting the gain required to make up for losses in apparatus and office cabling, the total gain is about 488 miles, the difference, 12 miles, representing the net equivalent. Evidently only a very small percentage change in either the transmission losses or the gains will have a large effect on the net equivalent. This represents about the most severe condition. Some examples of less severe conditions are—

2–Wire 19-gauge M.H.L. circuit 200 miles long (320 kilometers). Line equivalent 58 miles. Repeater gain exclusive of gain required to make up for loss in apparatus and office cabling 46 miles. Net equivalent 12 miles.

4–Wire 19-gauge M.H.L. circuit 500 miles long (800 kilometers). Line equivalent 145 miles. Repeater gain exclusive of gain required to make up for loss in apparatus and office cabling 133 miles. Net equivalent 12 miles.

In order to maintain the necessary constancy of the overall or net transmission equivalent of long repeatered circuits in cable, it is necessary first of all to maintain the gains of the individual repeaters within close limits. In addition, periodic transmission measurements are required over the complete circuits, supplemented by suitable adjustment of certain of the individual repeaters whenever the overall equivalent falls outside of the prescribed limits. Also, on the very long small gauge circuits, the changes in attenuation, due to the resistance changes caused by temperature variations, become so large that it is practically essential to provide automatic means for overcoming these effects.

The methods employed in maintaining the gains of the individual repeaters and of the overall transmission equivalents within proper limits will first be described, after which the automatic transmission regulators will be discussed.

VIII. Important Tests and Adjustments

In order to hold the repeater gains constant, close inspection limits are placed on the vacuum tubes during the course of manufacture to insure great uniformity of the product, as well as consistency of performance. In operating the repeaters, considerable care is taken to maintain constancy of the operating currents and voltages. The operating limits of currents and potentials together with the corresponding gain variations for one of the types of tube in common use are given in the following table:

Variable Quantity	Prescribed Limits	Gain Variation
Plate Potential	130 ± 5 volts	± .2 mile
Grid Potential	9 ± 1 volt	± .3 mile
Filament Current	1.25 ± .05 ampere	Very small for new tube—1 mile for tube just before replacement.

In addition to maintaining the tube currents and voltages within the required limits, the gains of the individual repeaters are checked periodically. Suitable adjustments are made when the repeater gains fall outside of the prescribed limits. When the filament emission of a tube becomes so low that the above specified variation in the filament current results in more than 1 mile gain variation the tube is replaced.

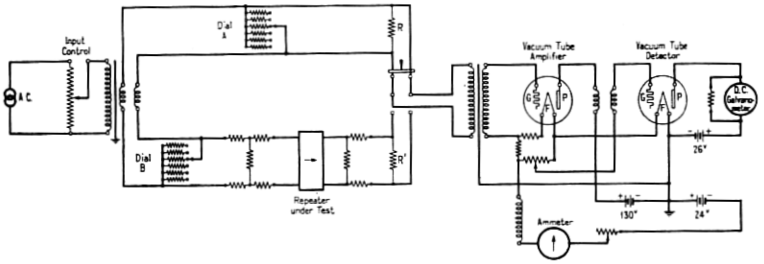

Fig. 14—Device for measuring telephone repeater gains.

A gain measuring device as indicated schematically in Figure 14 is employed for this purpose. The measurement of gain is effected by comparison of the voltages across two resistances, one of which forms part of a circuit which includes the repeater, the other being simply a reference circuit. An amplifier-detector combination amplifies the voltages across these resistances and then rectifies them so as to obtain an indication on a d.c. galvanometer. Equality of voltages across the two resistances, which are designated as R and R' in the figure, is thus indicated by equal deflections of the galvanometer. When this condition is secured, the repeater gain is read directly from the dials A and B. By means of this device, it is readily possible to measure the gain of a repeater within a few tenths of a mile. Owing to the fact that the measuring circuits are comprised entirely of resistances, the readings of the set are independent of frequency, so that gains can be measured at all important telephone frequencies.

As pointed out above, transmission measurements over the complete circuits including the telephone repeaters are required at periodic intervals in order to insure that proper transmission standards are being maintained. By means of such measurements, the variations in the overall equivalent of the circuits due to the cumulative effect of small gain variations, slight variations which remain after the automatic transmission regulators have compensated for the major variations in the conductors and variations from other causes including the effect of different conditions of humidity on the wiring in the offices, are determined and compensated for. These measurements are made by applying a known electromotive force through a known resistance to one end of the circuit and receiving the current at the distant end with a suitable calibrated arrangement employing an indicating meter. Since this type of measurement is similar in principle to the method employed for measuring the gains of the individual repeaters, it will not be described.

IX. AUTOMATIC TRANSMISSION REGULATORS

Since the resistance of long cable circuits employing small gauge conductors is comparatively large, it is, of course, evident that changes in this resistance caused by temperature changes to which the cable circuits are subject will have a large effect on transmission. For example, in the case of an X.L.L. 19-gauge 1000-mile circuit (1600 kilometers) in aerial cable, the total attenuation changes more than 110 transmission miles during the course of a year. This corresponds to a variation in the received power of more than 10^{10} or ten billion times.

It is, of course, essential to provide special means to counteract these effects. Furthermore, since the temperature changes which

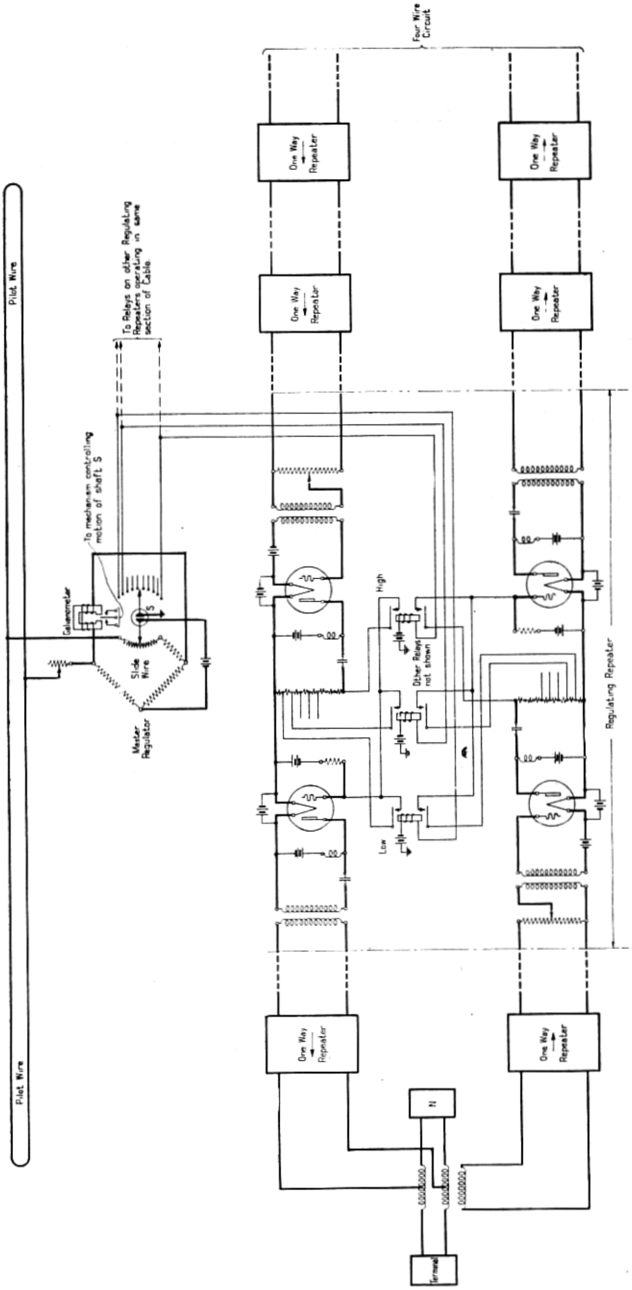

Fig. 15—Pilot wire automatic transmission regulator.

occur in an aerial cable are very rapid, it is practically essential to make these means automatic. In the case of X.L.L. 19-gauge circuits whose variation is greatest, it is necessary to locate the automatic regulators, in general, at every third or fourth repeater station in order to keep the transmission levels within proper limits. In Figure 1-a, a typical method of locating the regulating devices along a cable is indicated. In this sketch each square indicates a master automatic transmission controlling device while the loops extending in either direction from the squares indicate the cable circuits which control the functioning of these devices.

An automatic transmission regulator is shown schematically in Figure 15. The device comprises a Wheatstone bridge arrangement. In one arm of the bridge, pilot wire pairs, extending in either direction in the cable, are included as indicated in the figure. The Wheatstone bridge has associated with it certain apparatus which will not be described here in detail, which functions in such a manner as to automatically keep the bridge balanced at all times. In the process of maintaining balance of the bridge, angular motion is conveyed to a shaft which is proportional to the resistance variations which the cable circuits undergo. The movement of the shaft causes different contacts to be made and thus controls relays which in turn control the gains of the telephone repeaters, one way of doing this being indicated in the figure. The repeater gains are thus caused to be raised and lowered automatically, and thereby overcome the differences in attenuation caused by the temperature changes in the cable conductors.