

Nov. 17, 1931.

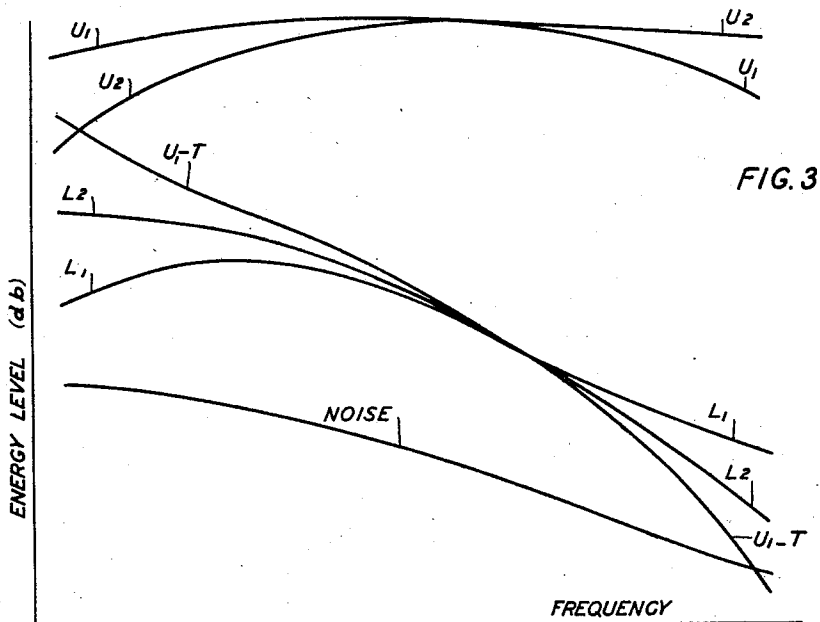
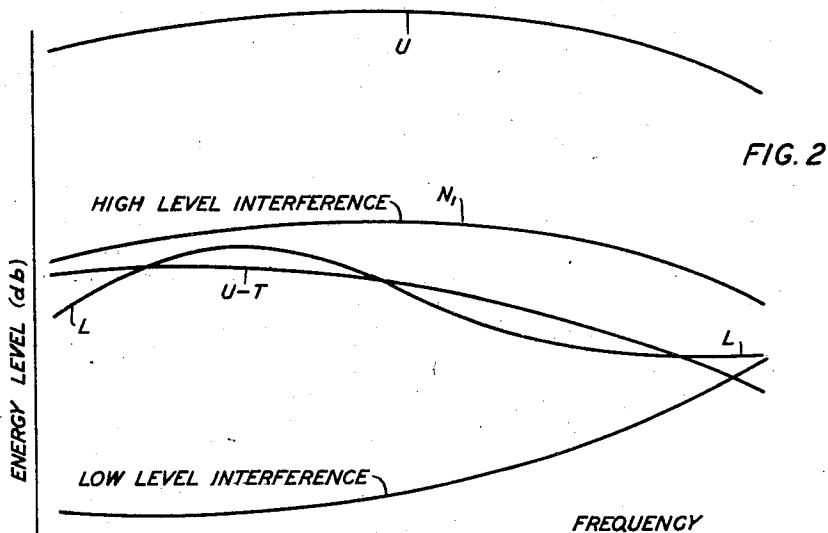
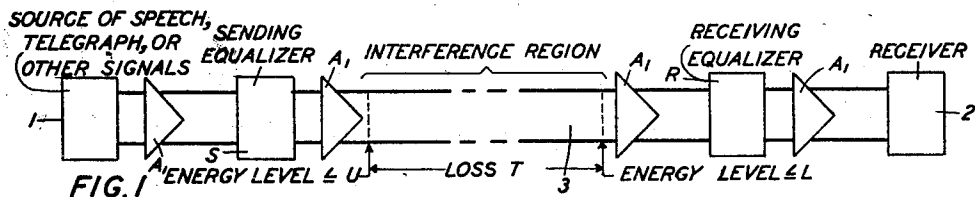
H. W. DUDLEY

1,832,366

ELECTRICAL COMMUNICATION SYSTEM

Filed July 8, 1930

3 Sheets-Sheet 1



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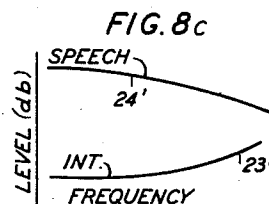
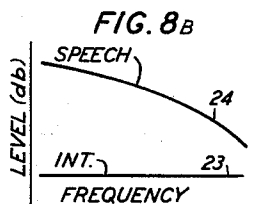
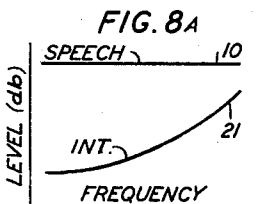
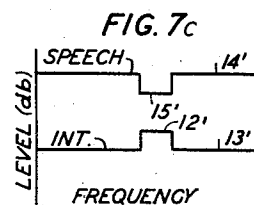
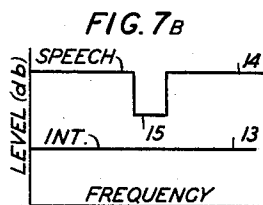
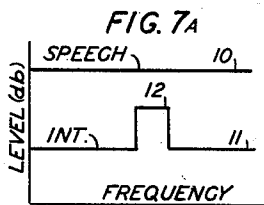
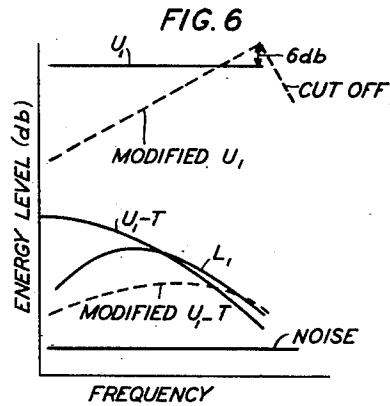
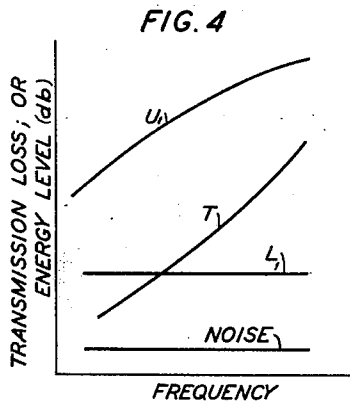
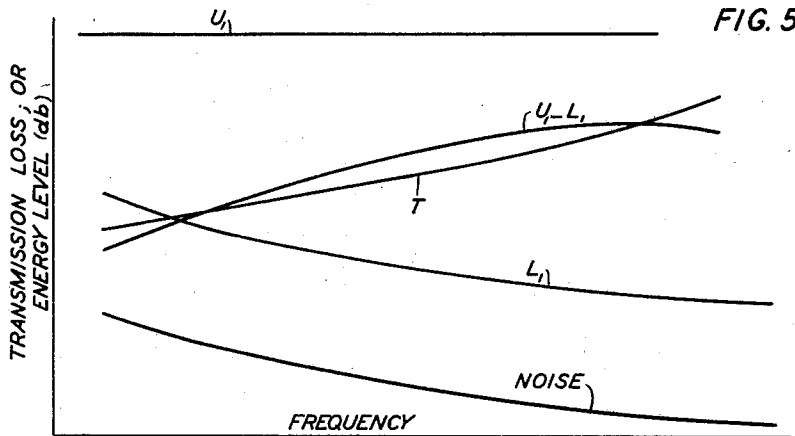
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ELECTRICAL COMMUNICATION SYSTEM

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3 Sheets-Sheet 2



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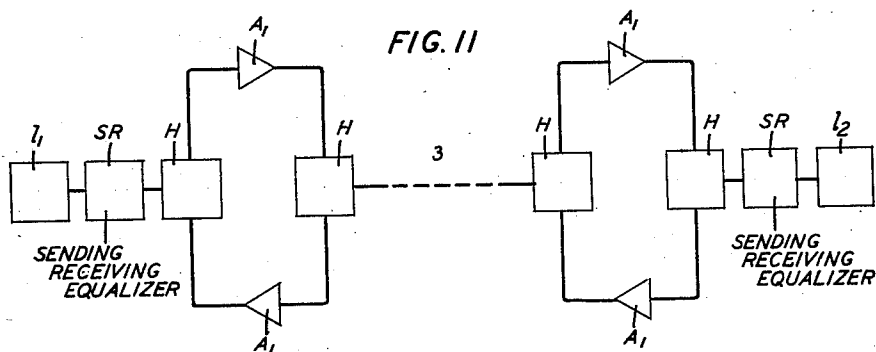
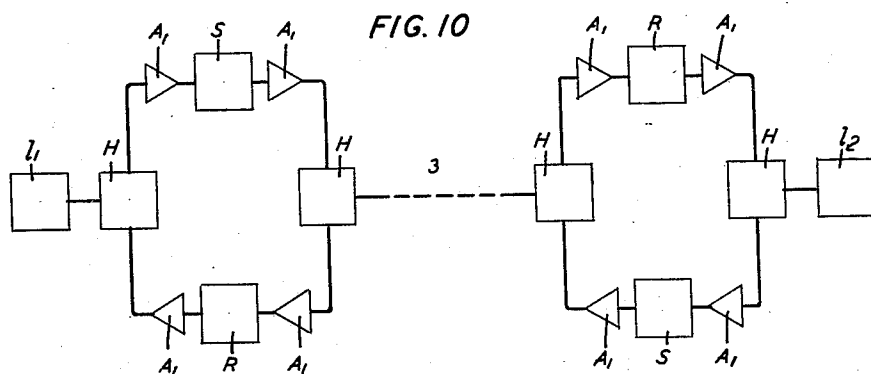
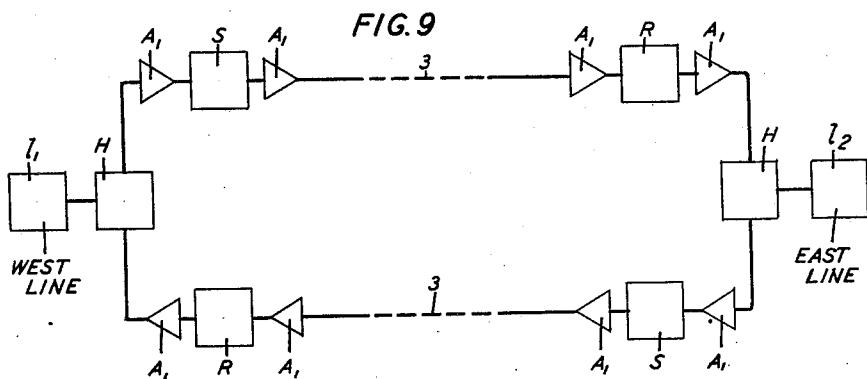
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ELECTRICAL COMMUNICATION SYSTEM

Filed July 8, 1930

3 Sheets-Sheet 3



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ELECTRICAL COMMUNICATION SYSTEM

Application filed July 8, 1930. Serial No. 466,460.

This invention relates to wave transmission systems, as for example, telephone systems.

Objects of the invention are to decrease deleterious effects of disturbing energy and to improve overall response-frequency characteristics.

Often signals must be transmitted through a noise or interference zone, that is, through a region in which noise or disturbing currents enter or are set up in the transmission system. Methods have heretofore been proposed to increase the signal-to-noise energy ratio obtaining at the receiver. One of these prior methods was to amplify the signal wave before transmitting it into the interference region. (Latour Patent 1,630,346, May 31, 1927; Hitchcock Patent 1,507,178, September 2, 1924.) The noise and signal after emerging from the interference region were attenuated sufficiently to reduce the signal energy level at the receiver to the desired value and to correspondingly reduce the noise energy level at the receiver. By this method, if the signal amplification (and therefore the margin of energy in favor of the signal) be sufficiently great, the noise energy can be reduced to a negligibly small value without effacing the signal. That is, the effect of the disturbance can be made negligible if sufficient energy is used at the sending end of the system and sufficient uniform or distortionless attenuation at the receiving end. However, limitation on the practice of such method is that restrictions are imposed on the sending energy. For example, in many systems a sending end amplifier or other transmitting apparatus is operated at its maximum permissible load (for the shape of the wave it is transmitting), regardless of disturbing energy that may enter or be set up in the system between the sending end and the receiving end. In such cases, if greater amplification of each frequency component be attempted, it is at the expense of distortion, and the system is then said to have become overloaded. That is, upon the increase of the power of each frequency component at the sending end the amplifying apparatus at that end (and in many cases other overloaded apparatus in the system) itself in-

roduces distortion or noise. This distortion limits the advantage to be gained from increasing the sending end power of each frequency component with the given apparatus. In other words it is of no avail to reduce the disturbing effect of a given interference energy if in doing so the system becomes so overloaded that, for example, because of harmonic generation (and other distortion frequency or distortion component generation), the signal suffers a degradation that more than off-sets the advantage of the reduction of the effects of the given interfering energy.

However, it has also been pointed out heretofore (Hartley Patent 1,737,843, December 3, 1929) that, even when the load limit of the sending apparatus has been reached (for the shape of the wave it is transmitting), the deleterious effects of noise upon the received signal can in many or most cases still be reduced, by changing the wave shape. The frequency distribution of signal energy or of time-averaged signal power sent from a transmitting station generally is not uniform. For instance, as indicated by the curve showing the energy frequency distribution of average speech, page 79 of H. Fletcher's "Speech and Hearing", D. Van Nostrand Company, New York 1929, the frequency spectrum of the energy of normal speech is not uniform; nor is it uniform after modification by the microphone or other sending apparatus. To the contrary, the time-averaged value of the power in speech is greater for some frequencies than for others. That is, the frequency spectrum of the signal contains frequencies of comparatively low energy level and frequencies of comparatively high energy level. (A high energy level occurring at any particular frequency region does not necessarily imply high sound intensities in the region, but may result from either a large number of speech sounds having low intensities in the region or a few sounds having components of high intensities in the region.) Moreover, it is usually the case that the frequency distribution of energy is different for the noise than for the signal, and that when the frequency

distribution of the noise energy is not uniform over the utilized frequency range, the maximum value of single frequency time-averaged power or of single frequency energy occurs at a different frequency for the signal than for the noise. A method heretofore proposed for so changing the wave shape of signals as to increase the amount that noise effects can be reduced, is to change the frequency distribution of the signal energy (as for example, speech energy) before the signal is sent through the sending end amplifier or other apparatus that otherwise might be too greatly overloaded.

According to this method heretofore proposed, this change in the energy-frequency relations in the speech before transmission may be effected by the use of a network having transmission-frequency characteristics such that the network discriminates against the transmission of components in the frequency regions of certain signal energy levels and in favor of the components in the frequency regions of certain other signal energy levels. (For example, it has been proposed that under certain conditions the frequency zones discriminated against be those in which the interference or noise energy to which the line is subjected is small and those frequency zones which the network favors be those in which the interference energy is relatively high.) A network at the receiver having a characteristic complementary to that of the transmitter network then restores the speech to its original energy distribution and at the same time attenuates the noise. It is found in practice, that an increase in intelligibility by the use of such complementary networks can be effected if the networks are given the proper characteristics. Instead of making the network at the transmitter and receiver exactly complementary, they may be so designed as to compensate for distortion in the system such as that due to unequal attenuation of the different signal frequencies. For example, if desired the overall system attenuation obtained by adding the individual attenuations of the transmitting and receiving terminal apparatus, and considering amplification as a negative attenuation, may be made the same for all frequencies in the entire frequency range which it is desired to transmit.

It has heretofore been proposed that the predistortion of the signal (that is, its distortion before it is transmitted to the interference or noise zone), be made such as to give it a distribution of energy with respect to frequency that is substantially the same as the distribution with respect to frequency of the noise to which the signal is subjected. A particular proposal has been that when the noise-producing interference has a substantially uniform distribution of energy with

respect to frequency, and before entering the interference zone it passes through vacuum tube amplifiers which have a limited load carrying capacity, the predistortion of the signal be made such as to obtain approximately the same energy level for all of its frequencies, in order to bring the energy level of each of its frequencies up to the maximum uniform energy level for the apparatus included in the system. (It has also been proposed that, to override a noise having a narrow frequency range, the predistortion of the signal be made such as to provide a particularly high signal energy gain for the interfering frequency range.)

As indicated above, then, it has already been proposed to override interference by increasing the sending energy of the signal and moreover, make the increase selective with respect to frequency so that overloading will be less than were the sending energy merely amplified uniformly over the unutilized frequency range; and as also indicated above, it has heretofore been particularly proposed to give the sending energy a frequency distribution like that of the noise energy, or equalize the sending energy to a flat energy-frequency characteristic when the limiting factor determining the sending energy is overloading of amplifiers and when the noise energy (or the average noise power) of each frequency in the utilized frequency range is substantially the same so that the interfering energy has a flat energy-frequency character. However, those proposals assume a fixed circuit loss and a fixed upper energy level at the different frequencies in the utilized frequency range. In accordance with the present invention, account is taken of the effect upon the overall transmission characteristics of a communication system which may be produced by varying its characteristics of transmission loss versus frequency, upper limitation on signal energy versus frequency, and lower limitation on signal energy versus frequency, and by means of the invention the most favorable relation between these three characteristics is established. For brevity, these three characteristics will be referred to herein as T, U, and L, respectively. T is the loss between the portion of the system in which U occurs and the portion in which L occurs.

In accordance with the invention it is proposed to send the power into the exposed region with such a frequency characteristic that the interference (if any) set up at the high level end of the system, (as for example, interference set up by overloading) is of the same order, measured in interfering effect, as is the interference picked up at the low level end of the system. In particular, for the case of speech it is proposed to take account of interfering effect and consequently, in view of variation with frequency in dis-

turbing effect of a given amount of single frequency energy, permit interference levels relative to speech to vary considerably over the frequency range.

5 The fact that in any system there must be an upper limitation on energy is obvious since transmission of infinite energy would, of course, entail infinite expense. However, with sufficient money expenditure any practical system can be so improved as to permit
10 U to be raised advantageously as regards the quality of the received signal. The limiting factor that primarily determines U may be, for example, overloading, either because of the limitation it places on the volume of energy transmitted or on account of the har-
15 monics set up. (Overloading presupposes a non-uniform input-output relation.) This overloading may occur where the energy levels are high, as in sending terminal apparatus or in repeaters, or may occur in loading material or other magnetic material because of hysteresis effects. Usually it occurs at a point in the system which the transmission reaches
20 before being greatly attenuated by the transmission loss between the sending end and the receiving end of the system. In general, the characteristic U is approximately flat when the limiting factor that primarily determines it is overloading or is heating of conductors, or is cost of power (in vacuum tube systems, at least), or is dielectric strength of materials. When the limiting factor determining this characteristic for a circuit is transfer of energy to other circuits, that is, production of
30 cross-talk or noise in other circuits, in general this characteristic is not flat but slopes in many cases in such a way as to indicate that less energy can be transmitted at the higher frequencies in the utilized range than at the lower frequencies, for equal interfering effects. In the case of eddy current shielding, however, the slope is usually the reverse.

The lower limitation on energy L, is usually set primarily by the amount of external energy picked up as noise or cross-talk. In a recording-reproducing system the noise is from the record chiefly. In all communication systems, the lower limitation L is, in
50 general, primarily set by noise in some form or other. In any case, there must apparently be some limitation, because if extremely low energy values are approached the directness in the construction of the matter employed and the current caused by thermal agitation of electrons becomes of consequence. In the case of telephone-circuits, noise sources other than thermal agitation are: superimposed or adjacent carrier circuits, adjacent power cir-
60 cuits, common impedance circuits, Schrot effect, static, etc.

The characteristic T, for transmission lines for instance, depends on the attenuation. The attenuation is a function of the line constants
65 (resistance, distributed or lumped induct-

ance, capacity and conductance) and of the amplification, if any. In a recording-reproducing system, this characteristic would be the loss from some conveniently chosen point in the recording device to some conveniently
70 chosen point in the reproducing system.

In general, by sufficient expenditures along the proper lines for improving a system, not only can its characteristics U be raised but its characteristics T and L can be lowered.
75 For instance, a slight improvement in the transmission loss versus frequency characteristic obtained by decreasing the resistance of conductors usually gives an incremental improvement at each frequency in the grade of transmission. It may be that economy would result from improving any of the three characteristics. On the other hand, it may be economical to degrade any of them. For all transmission systems of any given general type affording a given grade of transmission there is a relation between the three characteristics U, L and T which results in the cheapest system of the given type that will afford a given grade of transmission. (Ex-
80 amples of systems that differ in type as the term-type is here used are a radio telephone system and a submarine telephone cable.) When this relation exists the system may be said to be in economic equilibrium as regards
85 these three characteristics.

For any given signaling system, in which increased input interferes with intelligibility, as for example, a given speech transmission system, there is a characteristic of upper limit of message energy, versus frequency, such that, were the predistortion of the message energy such as to obtain this latter characteristic, all of the frequency components of the signal energy (or all narrow frequency bands of the signal energy of equal width) in the utilized frequency range would contribute predetermined equal amounts to the deleterious effect upon the selected standard of signal quality (as for example, upon intelligibility or upon naturalness) that would result from the greatness of the magnitude of the upper limit of signal energy at the various frequencies in the utilized frequency range. The deleterious effect could result from the greatness of the energy magnitudes because of any of various limiting factors. Examples of such factors, including overloading, are given above. For brevity, this characteristic
100 will be designated U_1 . U_1 will depend on the desired quality. The higher the desired quality the less U_1 will be. The actual energy versus frequency characteristic of the sending energy (i. e., the characteristic of the actual upper limit of the message energy versus frequency), will be designated U_s , for brevity.
105

Exact determination of the characteristic U_1 may be difficult in particular cases, be-
110 120 125 130

cause the energy level of any given frequency that would result in the predetermined contribution to the interfering effect is not independent of the energy level at other frequencies. However, by assuming such independence, a characteristic can be determined readily which is a close approximation to the characteristic U_1 . For brevity, this approximate characteristic will be designated U_1' . By then taking account of the errors involved in the assumption of the independence just mentioned, from U_1' the characteristic U_1 can be determined to the requisite degree of accuracy.

For any given signaling system, as for example, a speech transmission system, having any given characteristic of interfering energy versus frequency, there is a characteristic of lower limit of message energy versus frequency, such that, were the predistortion of the message energy such as to obtain this latter characteristic (with the given T of the system), the loss of signal quality resulting from the disturbing energy of one frequency of the utilized frequency range would be a predetermined amount, equal to the quality loss resulting from the disturbing energy of any other frequency of the utilized range. For brevity, this characteristic will be designated L_1 , and the characteristic of the actual lower level of message energy versus frequency will be designated L_2 . L_1 will vary with the quality desired, it being higher for better quality.

In one specific aspect the invention is a signaling system in economic equilibrium as regards U , L and T .

In another specific aspect the invention is a signaling system having means for rendering its characteristic U_2 substantially the same as, or more nearly of the same form as its characteristic U_1 , regardless of what the form of U_1 may be and regardless of the frequency distribution of the disturbing energy to which the signals are subjected and the resulting characteristic L_1 . For example, the characteristic U_2 of the message energy may be made to approach the characteristic U_1 when U_1 is not flat but is, for instance, of the form mentioned above as resulting from its determination by the limiting factor of cross-talk into other circuits, or is, for instance, of a form mentioned hereinafter as resulting from its determination by the limiting factor of modulation effects; and moreover, such approach to a characteristic U_1 that is not flat may be caused either when the frequency distribution of disturbing energy to which the system is subjected and/or the resulting characteristic L_1 is flat or is not flat, and further, may be so caused either when T is flat or when it is not flat. By the way of further example, the form of the characteristic U_2 of message energy may be made to approach that of the characteristic U_1 when L_1 is not

flat and either when U_1 is flat or when it is not.

In another specific aspect the invention is a signaling system in which the value of U_2 is chosen so that the definitely determined interfering effect received by the distant subscriber (or recording instrument) due to high energy level effects balances the definitely determined interfering effect due to the low energy level effects in such a way as to make for a minimum total interfering effect. In many cases this will mean that equal interfering effect results from the high level and low level interference. In such cases U_2 is a compromise between U_1 and $(L_1 + T)$.

In still another specific aspect the invention is a signaling system in which U_2 is set for other than intelligibility reasons, for example a breakdown voltage limit, in which case there is a variety of choice of U_2 for multi-frequency signals and U_1 is chosen to fit the particular U_2 that leads to minimum interference effect due to low level energy.

If U_2 and L_2 could be made the same as U_1 and L_1 respectively, at the same time, then each small or elemental frequency band of energy in the utilized frequency range would contribute equally to the degradation of signal quality, the degradation resulting from both the limiting factor that primarily determines U_1 and the limiting factor that primarily determines L_1 . This ideal case is then very simple. However, this usually is not practicable; for practical considerations limit the degree to which it is feasible to control U_1 , T and L_1 . Therefore, it is often desirable to make U_2 depart somewhat from U_1 in order that L_2 may approach L_1 more closely. For example, when the characteristic obtained by plotting $(L_1 + T)$ versus frequency lies above the characteristic U_1 at some frequencies, or in other words when the characteristic obtained by plotting $(U_1 - T)$ versus frequency lies below the characteristic L_1 at some frequencies, then U_2 is made a compromise between U_1 and $(L_1 + T)$. In general, the compromise value of U_2 is made substantially the average of U_1 and $(L_1 + T)$ at each frequency, unless U_1 and $(L_1 + T)$ differ considerably in which case U_2 is taken with due regard to the fact that a great increase in decibels can be made in a small quantity without making it appreciable compared to a large quantity.

A feature of the invention is the reduction of masking effects of interfering waves of given frequencies in the utilized frequency range upon signaling waves of neighboring frequencies in that range, by discriminating against transmission of the interfering waves and the signaling waves of the given frequencies relative to transmission of waves of the neighboring frequencies. This method does not depend upon alternating the ratio of signal energy to noise energy at any frequency, but reduces masking effects suffi-

ciently to thereby yield a greater advantage than is lost by the frequency distortion produced.

Another feature of the invention relates to economizing equalizers or networks having non-uniform frequency-response characteristics. It has been found that for certain typical communication telephone circuits, there is little difference between the transmission loss-frequency characteristic of the equalizer that would be required to convert the electrical output of the telephone subset to one uniform over the equalized frequency range and the transmission loss-frequency characteristic of the equalizer that would be required at the subset to render the air-to-air transmission loss-frequency characteristic of the system flat (assuming the two ends of the system alike as regards equalizer equipment). Therefore, in accordance with the invention, the average of the two characteristics may be taken as the characteristic to be used for both the equalizer for the sending end energy and the equalizer for the receiving end energy, and then instead of employing a separate sending and receiving equalizer at each end of the circuit, only one equalizer need be employed at each end, the one equalizer serving as both the sending end equalizer and the receiving end equalizer for that end of the system, when sending from that end and receiving at that end, respectively.

Other objects and features of the invention will be apparent from the following description and claims.

Fig. 1 of the drawings is a circuit diagram of a one-way signal transmission system embodying a form of the invention;

Figs. 2, 3, 4, 5, 6, 7A, 7B, 7C, 8A, 8B and 8C show curves for facilitating explanation of the invention;

Fig. 9 shows a four-wire system embodying a form of the invention;

Fig. 10 shows a two-way two-wire circuit embodying a form of the invention; and

Fig. 11 shows another form of two-way, two-wire circuit embodying a different form of the invention.

Fig. 1 shows a system including a source 1, of signal energy (as for example, a telephone transmitter), some of which is to be transmitted to a signal receiving circuit or means 2 (as for example, a telephone receiver) over a path or transmission medium which includes in some portion of it at least one region of exposure 3. (For example, a single region of exposure is shown.) Before this region of exposure are sending end equalizer S and one-way amplifiers A₁, and after the exposure are receiving end equalizer R and one-way amplifiers A₂. Such a system may have its characteristics U, L and T, referred to above, as shown in Fig. 2, for example. The lower limitation L is determined in view of the effects of the exposure

for the standard of transmission required; thus, if noise is picked up the speech or other signal energy must be kept above a certain level as compared to the noise or intelligibility will be impaired too much. Between the sets of equalizers and amplifiers, is the transmission loss T which is a definite quantity of known characteristic for any given type of system. Somewhere in the system the upper limitation on energy level, U, is present, either in the sending end amplifier or in a portion of the system in the exposed region, presumably in the first part of it before the energy level has been attenuated by a portion of the transmission loss T. If this upper limitation U is set primarily by some limiting factor that degrades the signal (for example if it is primarily set by modulation), then the level of the signal energy that primarily determines U (for example the energy of the modulation products) can be represented by some such curve as N'.

As indicated above, any of the characteristics U, L and T can be varied to improve the quality or figure of merit of the system, by varying properties of the system upon which depends the cost of the system. An example noted above is an improvement in T obtainable by decreasing the resistance of conductors. As noted above, a slight improvement in this respect usually gives an incremental improvement at each frequency in the quality or figure of merit of the system. T can be represented by a family of curves, each successive curve corresponding to increased expenditure and to increased improvement; similarly with U and L. The definite relation of U, L and T that, as noted above, yields any given value of quality or merit of the system with a minimum value of cost, or in other words, with the system in economic equilibrium, obtains when the improvement of the characteristics or variables U, L and T has been carried as far in the case of each individual variable as is required to give a common rate of change of cost with quality or merit.

Let \$ (U, T, L) = cost of system as a function of U, T and L; and Q (U, T, L) = quality or merit as a function of U, T and L.

Then economic equilibrium exists when

$$\frac{\partial \$}{\partial U} \frac{\partial U}{\partial Q} = \frac{\partial \$}{\partial T} \frac{\partial T}{\partial Q} = \frac{\partial \$}{\partial L} \frac{\partial L}{\partial Q}$$

These equations give two independent relations between U, T and L. We can get from them then, relations giving U and L as functions of T when the system is in economic equilibrium. These values of U and L in terms of T can be substituted in \$ and Q making them functions of a single variable. By determining \$ and Q for common values of T the curve of \$ and Q for systems in economic equilibrium is obtained. If U, T or L can be varied in a number of ways to

obtain improvement, each method of variation should be considered. Thus suppose U can be varied in r ways, T in s and L in t giving r families of U curves, s of T and t of L then the above equations become

$$\begin{aligned} \frac{\partial \$}{\partial U_a} \frac{\partial U_a}{\partial Q} = \frac{\partial \$}{\partial U_b} \frac{\partial U_b}{\partial Q} = \dots = \frac{\partial \$}{\partial U_r} \frac{\partial U_r}{\partial Q} = \frac{\partial \$}{\partial T_a} \frac{\partial T_a}{\partial Q} = \\ \dots = \frac{\partial \$}{\partial T_s} \frac{\partial T_s}{\partial Q} = \frac{\partial \$}{\partial L_a} \frac{\partial L_a}{\partial Q} = \dots = \frac{\partial \$}{\partial L_t} \frac{\partial L_t}{\partial Q} \end{aligned}$$

The process discussed here may become complicated if an attempt is made to set up the equations of the general systems. However, graphically it is relatively simple to consider pairs of values U' U'' ; T' T'' ; L' L'' , such that each pair corresponds to about the same increment of cost or quality and compute the other increment. If the ratio of the increment is approximately the same then the system is near the economic equilibrium point while if one ratio is materially different from the others, a cheaper system of the same Q is obtainable by properly adjusting the values of U , T and L .

The system such as that shown in Fig. 1 may be, for example, a submarine telephone cable system having its U_1 , L_1 , T , U_2 characteristics, referred to above, of the form indicated in Fig. 3. In determining the U_2 characteristic to use for designing the sending end equalizer for a given system which has a given T characteristic, it should be borne in mind that, although the system usually is such that it is not practicable to have $(U_1 - T)$ equal to L_1 , ideally that relation should obtain: for then U_2 could be made equal to U_1 , and consequently $(U_2 - T)$ would equal L_1 or, in other words L_2 would equal L_1 . The equality of L_2 and L_1 would mean that at each utilized frequency the actual low value of message level was just high enough to keep within the desired limit the contribution of the low level noise energy of that frequency to the signal degradation; and the equality of U_2 and U_1 would mean that at each utilized frequency the actual upper value of message energy was just low enough to keep within the desired limit the contribution that the greatness of the magnitude of the message energy of that frequency caused to be made to the signal degradation. The ideal condition is that in which L_2 equals L_1 , U_2 equals U_1 and approximately equal signal degradation results from the limiting factor (for example overloading) that primarily determines U_1 and the limiting factor (for example interference) that primarily determines L_1 . If at each instant the impressed signal electromotive or other force at the point of exposure were sinusoidal, then the U_1' and L_1 curves could readily be determined. The limitation L_1 is primarily set by interference pick-up and consequently L_1 should be at each frequency a certain num-

ber of decibels above the energy that would be masked by the interference, this number depending on the desired standard. If this number of decibels cannot be obtained at each frequency then it must be effectively obtained over the frequency range by having sufficient excess or improvement at some frequencies to make up for the deficiency at other frequencies. When U_1 is primarily determined by overloading, U_1 (which is the same as U_1' where only one frequency is present at a time) would be determined by the amount of overloading of the system permissible to the ear or other intelligence receiving device, taking into account the variation that the receiving device given in quality of transmission for the same amount of overloading at different frequencies and also the difference that the receiving device requires in masking ratio at different frequencies for a given figure of merit.

For the case of signal energy such as that from speech or music, at any instant instead of a single frequency, a set of harmonic frequencies is present except, of course, during the silent intervals. For any given system the value of U_1 at any frequency is now dependent to some extent at least on its value at other frequencies. Thus, if it is important that a given frequency be received in good volume, then this result may be attained to a slightly greater extent if the energies at other frequencies are decreased somewhat. To simplify the problem let us first assume that this effect is negligible (Case I) and then take account of the changes required for the actual conditions (Case II).

Case I—The value of U_1 at any frequency assumed to be independent of the values allowed for other frequencies, i. e. $U_1 = U_1'$.—For speech, then, the desired sending end equalizer characteristic is obtained as follows: The energy-frequency characteristics of all sounds to be transmitted are plotted and an envelope drawn over these. The equalizer of minimum loss capable of correcting this envelope to the shape of U_1' is then designed. Next, sufficient amplification is added to bring the level up to U_1' . For transmission of signal energy other than that of speech a corresponding procedure would be employed so that detailed discussion for such cases is unnecessary. Several questions arise in this procedure under this Case I, which will be discussed below:

1. It is impossible to get energy-frequency characteristics of all sounds by all people, so something that is fairly representative must be taken. The spectrum of energy versus frequency for four male and two female voices as given by Crandall and MacKenzie in the Physical Review, March, 1922, pages 221 to 232 was used in a particular design which led to very good results. This is a satisfactory procedure. The spectra on a large number

of voices would, of course, be very desirable whether the average or the envelope be taken. As it is only the curve shape (and not the absolute values) that is of importance here, the average and envelope values lead to designs that do not differ very much. If it be assumed that different frequencies have practically the same distribution of relative levels, then either average or limiting energies lead to the same results. This assumption while not precise, is satisfactory for the practical design of the sending end equalizer.

2. The proper standard to set is in general one on the basis of intelligibility but sometimes one on the basis of naturalness or a compromise between intelligibility and naturalness. This would bring in the question of the frequency of occurrence of the different sounds and also perhaps the listener's familiarity with them. Accordingly, it would be very difficult to follow this procedure precisely. However, for practical purposes approximately this is effectively done when the average curve of energy versus frequency is taken for a large number of speakers for connected speech, because then unusual characteristics of individuals as well as uncommon energy distributions due to unusual words are averaged down.

3. After equalizing and amplifying, the desired characteristic U_2 is obtained. (This does not mean for a uniform characteristic that in speech energy corrected to this energy-frequency characteristic, at any instant the distribution of speech power over the utilized frequency range is uniform. However, it signifies that the distribution will be more nearly so than in the present commercial telephone systems. If the frequency distribution of instantaneous speech power did not change from instant to instant, there would be nothing to differentiate the various temporal energy elements, and consequently no intelligibility could be transmitted except by the effect of starting and stopping energy flow). When the limiting factor determining U_1 for a circuit is transfer of energy to other circuits, that is, production of cross-talk or noise in other circuits, in general this characteristic is less flat than when primarily determined by overload, and slopes in many cases in such a way as to indicate that less energy can be transmitted at the higher frequencies in the utilized range than in the lower frequencies, for equal interfering effects, i. e. for equal intelligibility contributions to the disturbed circuit at each utilized frequency.

The relative contribution of vowels and consonants to the standard of quality established is of some importance. Vowels are received satisfactorily in general on account of higher energy levels and energy concentration at the lower frequencies. The design can be made to help the consonants at the ex-

pense of the vowels, if it is desired to increase intelligibility at the expense of naturalness. The energy for consonant sounds at most frequencies below 3,000 cycles is considerably less than that for vowels. At higher frequencies the energy of the consonant sounds is relatively more important. Thus, some slight gain in intelligibility can be introduced by an equalizer design based on energy distribution in consonant sounds. However, increase of intelligibility with such a system is at the expense of naturalness of sound and therefore such a system is not desirable in most cases.

In Case I (as in the case of transmission of a single frequency at any instant), when the upper limitation is not such as to produce interference energy that degrades the signal (for example when the upper limitation is a voltage limitation because of dielectric properties of insulating material), the sending end equalizer plus amplifier system has been determined by two things only: (a) The energy level of the signal at each frequency upon reaching the beginning of the exposure; and (b) The characteristic U_1 at this point. Thus, in this case, as well as in the case of single frequency transmission at any instant, the design of the sending end equalizer is determined completely by conditions existing at the beginning of the exposure. In particular, it is noted that the transmission loss characteristic over the exposed region (that is, the characteristic T) does not affect it nor does the limiting factor (for example, interference) that primarily determines L_1 . If the receiving end equalizer is designed to give, in conjunction with the sending end equalizer, a certain air-to-air characteristic, either flat or typical of similar circuits, then the receiving end equalizer characteristic is also determined independently of that limiting factor, so that the design of the optimum equalizing arrangement for minimizing the effect of that limiting factor is independent of that limiting factor, the sending end equalizer being also independent of the loss T over the region of exposure.

Case II—Actual speech transmission.—In the case of speech transmission the assumption that for the characteristic U_1 the energy level for each frequency is independent of the levels for the other frequencies gives a very good first approximation, so that we can consider the procedure as that of determining the two equalizer characteristics (i. e., the sending equalizer characteristic and the receiving equalizer characteristic), as discussed under Case I and then modifying these slightly as discussed later to fit better the speech transmission circuit in the particular problem. From computations of the energy components of representative vowel sounds, it appears for the vowel sounds

that after correction to give a uniform (i. e., flat) characteristic, the differences between the total energy of the vowel sound (that is, its energy over the whole utilized frequency range) and the maximum energy of the vowel sound at any single frequency averages approximately 6 decibels. From this figure it is seen that the error of the assumption, (Case I above), that the equalizer loss value at any frequency was to be chosen as though energy at other frequencies did not affect the proper value of equalizer loss at that frequency approximates an average of about 6 decibels. This is not very large. When the transmission loss T in the region of exposure and the lower energy limitation L_1 are of such nature as to permit utilization of most of this amount, the correction would be more important than is the case in many systems where only a small fraction is obtainable.

Fig. 6 shows a typical example of a way in which, in improving transmission (decreasing the effect of noise) in a system having a characteristic U_1 of a given shape, an advantage can be obtained by giving the sending energy level a characteristic U_2 of different shape instead of the same shape. For example, the characteristic U_1 is shown approximately flat, the attenuation T is shown increasing with frequency and the low level interference is shown substantially flat. If the speech energy is flat at the sending end of the exposure it will slope off at higher frequencies after traversing the exposed region. This is indicated by the solid lines U_1 and $(U_1 - T)$. Some gain then can be obtained by transmitting the higher frequencies at slightly higher level, at the expense of appreciably lower levels for the lower frequencies. The dotted curves labeled modified U_1 and modified $(U_1 - T)$ indicate this. In this case at the high frequency end masking is serious. Some improvement is gained here although this in part offset by increasing masking at the low frequency end. However, as the masking was at a much lower level at the low frequency end, some net gain is obtained. The gain in a circuit of this sort by making the sending energy level other than flat is evidently less than the average figure (6 decibels) given previously. Some rough estimated figures for a submarine cable falling in this case might be 6 decibels higher level peak at the sending end equalizer and a net effective gain, taking account of the change of masking of perhaps two decibels, so that the net gain from this correction is not very large. When the limiting factor that primarily determines L_1 has a very decided peak over certain narrow frequency ranges, then more gain can be expected in these ranges due to these corrections, since at other frequencies the energy can safely be attenuated until it is negligible

in quantity, thus permitting the realization of the 6 decibels gain. Approximately two decibels more may be realized in those cases in which the effect of the changed spectrum, at the point of the circuit where the limiting factor that primarily determines the U_1 enters, is to permit more energy for the same loss of intelligibility or other standard of performance. Similarly, in other cases the opposite effect may cause a loss of approximately two decibels. As an example, if the disturbing effect of the third harmonic produced by overloading is the limiting factor that primarily determines the U_1 in a speech transmission system then the peak at 3000 cycles would have less harmful effect than a peak at a lower frequency, since the harmonics would be produced in a range in which there is little speech energy, while a peak at 350 cycles would have more harmful effect as the third harmonic would occur in a most valuable speech region. Another effect to be considered in designing the equalizers is the shape of the masking curve. In general, interference energy at any frequency masks not only intelligibility from that frequency, but also that from others, particularly, from those adjacent. If the masking curve is higher in some frequency range we may infer that interference energy in that range is higher and is therefore masking the contributions of adjacent frequencies. The receiving end equalizer R can be designed to give additional loss over this frequency range in order to obtain some net advantage, that is, to obtain more advantage from the decreased masking at the adjacent frequencies than is lost by increasing the frequency distortion. By this method we do not change the signal to noise ratio at any frequency, but decrease the masking of frequencies that are adjacent to the high magnitude noise frequencies. Examples of this are shown in Figs. 7—A, 7—B and 7—C for an ideal case of a frequency range of heavy interference pick-up and in Figures 8—A, 8—B and 8—C for the common commercial case of interference increasing with frequency.

In Fig. 7—A the curve 10 for received energy level of speech shows the speech energy flat as it approximates over a limited frequency range in a high quality system. Portion 12 of the curve 11 for received energy level of interference shows a frequency range of high interference level in the utilized speech frequency range. A gain in intelligibility is obtained by sufficiently attenuating in the receiving equalizer R over this frequency range (or by shaping the energy curves in the receiving end amplifiers and equalizers) to flatten the received interference energy so that the received interference energy will be as shown by curve 13 in Fig. 7—B, as then the interference en-

ergy, in the frequency range in which it had the higher level shown at 12 in Fig. 7—A, no longer has that high level, but is sufficiently low to not greatly mask the adjacent utilized frequencies, whereas in Fig. 7—A there would be appreciable masking of the frequencies just above and below the high level portion 12 of curve 11. The equalizer attenuation (or the receiving amplifier and equalizer correction) which flattens (or changes) curve 11 to curve 13 also changes curve 10 to curve 14, which has a depressed portion 15 over the frequency range of the high level portion 12 of curve 11.

Fig. 7—C shows a lesser correction than Fig. 7—B. Curves 13' and 14' correspond to curves 13 and 14. Curve 13' has an elevated portion 12' over the frequency range of portion 12 of curve 11; and the receiving equalizer attenuation, being insufficient to entirely remove the elevation 12 from the interference energy level curve, produces a speech energy level curve 14' that has a depression to 15' less deep than the depression 15 in the speech energy level curve 14.

Figs. 8—A, 8—B and 8—C correspond, respectively, to Figs. 7—A, 7—B and 7—C, but in Fig. 8—A curve 21 shows the interference energy increasing with frequency, typical of many commercial systems. A gain in intelligibility is obtained by sufficiently attenuating in the receiving equalizer R (or by shaping the energy curves in the receiving end amplifiers and equalizer) to flatten the received interference energy so that the received interference energy will be as shown at 23 in Fig. 8—B, as then the high frequencies in the utilized frequency range have sufficiently low interference energy to not greatly mask the lower frequencies in the utilized frequency range, whereas in Fig. 8—A there would be appreciable masking of those lower frequencies. The receiving end correction which flattens or changes curve 21 to curve 23 also changes curve 10 to curve 24.

Fig. 8—C shows a lesser correction than Fig. 8—B. Curves 23' and 24' corresponding respectively to curves 23 and 24 as curve 13' and 14' correspond respectively to curves 13 and 14. The best results are obtained when the signal degradation caused by the added overall signal distortion equals that caused by the interfering waves that remain after the insertion of the additional attenuation, and equals that arising from the upper limitation interference energy when there is such energy.

As to the attenuation characteristic of the receiving end equalizer R, it is to be observed: (1) To give the system a flat air-to-air characteristic, the transmission characteristic of the receiving equalizer R is such that the sending end acoustic correction is removed and the rest of the system from the sending

end of the exposure to the listener is corrected; (2) To give the system the same air-to-air characteristic as a corresponding system with no region of exposure, the receiving equalizer R is complementary to the sending end equalizer and contains in addition equalization for transmission over the range of exposure; and (3) A condition between these two conditions is sometimes desirable. In particular, the compromise between flat speech level and flat masking level for the observer as discussed previously is often desirable.

The specific form indicated by Fig. 3 for the U_1 , L_1 , T and U_2 curves is merely illustrative. The system of Fig. 3 may be a system having various other forms of these curves. For example, instead of being a submarine telephone system having its U_1 and L_1 curves non-uniform with respect to frequency, as indicated in Fig. 3, it may be a submarine telegraph cable with characteristics such as those shown in Fig. 4 or a telegraph land line with characteristics such as those shown in Fig. 5.

In Fig. 4, L_1 is flat and T and U_1 rise with frequency. L_1 may here be determined primarily by a uniform noise energy level indicated in Fig. 4. With such a noise level the characteristic U_1 may be substantially flat since the receiving device may be an ordinary type of telegraph relay. U_1 may here be determined primarily by cross-talk to adjacent cables. In Fig. 5 L_1 falls with frequency rise. T rises with frequency and U_1 is substantially flat. L_1 may here be determined primarily by a noise energy level which decreases with frequency as indicated in the figure, the receiving device being a telegraph relay. U_1 may here be determined primarily by amplifier overloading.

Two purposes can be served by equalizing an exposed system; (1) Improvement of the air-to-air response characteristic and (2) Decrease of the effect of the interference energy pick-up in the exposed region. The "exposed region" in a portion of the circuit where the energy level of interference or, more strictly, a masking level is not sufficiently low compared to the level of the communication energy at that portion. Thus, in a system having considerable attenuation it may be that the interference energy pick-up is greater in other portions than it is in the portion where the interference energy is a limiting factor. In other words, it is not the absolute level of the interference energy, but its relative energy at different frequencies compared to the intelligence-transmitting energy that must be considered. Circuit limitations, particularly singing greatly affects the choice of networks and would often make desirable an arrangement that otherwise is not. In some cases the problem is one of fitting the corrective network in a circuit al-

ready in existence without disturbing its stability. In other cases, a design of a new circuit is to be made with the correction network as a portion of it. In the latter set of cases, there is more latitude.

As indicated above, in general the corrective network at the sending end and at the receiving end will consist of circuits for equalization and amplification. As indicated in Fig. 1, it is sometimes desirable both to use an amplifier before the equalizer so that the equalizer does not attenuate the energy to too low a level and to use an amplifier after the equalizer so that the amplifier will not need to carry too large a load. In general, at the receiving end, an amplifier will be used before the equalizer to build up the energy level before it is attenuated further. In many cases a single amplifier will be sufficient, particularly at the receiving end where the level required may be less than at the sending end. Figs. 1 and 9 to 11 shows circuits with a sending end or receiving end or combination type equalizers, S, R or SR respectively. The sending end equalizer S is to be designed so as to give energy equalization to correspond with U_1 at the beginning of the exposure. The receiving equalizer R is to be designed for one of the three purposes: (1) To correct for the rest of the circuit so as to give a flat overall characteristic (R_1); (2) To compensate for the loss characteristic of the sending end equalizer (R_2); (3) Something intermediate between R_1 and R_2 (R_3). The several circuits are discussed below:

I. Simple one-way circuit, Fig. 1.—In this case the circuit is preferably suitable if properly designed so there are no limitations on circuits developing as in practice this corresponds to program transmission circuits. These are already of high quality so that the possible improvement is not so great as in circuits used in commercial telephony, but on the other hand any improvement is, of course, much more valuable relative to the number of circuits involved.

II. 4-wire circuits, Fig. 9.—Most long distance two-way circuits are four-wire in part. Much greater total amplification is then possible for a given intelligibility, and a region of exposure may occur in one or more likely both of the one-way branches. Fig. 9 indicates the insertion of the equalizers of Fig. 1 in each of the one-way branches of the 4-wire circuit extending between lines L_1 and L_2 . For convenience the lines L_1 and L_2 may be regarded as a line west and a line east, respectively. Hybrid coil (bridge transformers) or other means for changing from one-way to two-way transmission and vice versa are shown as blocks designated H. Three cases to be distinguished here according to the type of receiving end equalizers used are: (1) If R_2 is used the net loss in either branch is unchanged and therefore the circuit sta-

bility is not affected; (2) If R_1 is used there is a net gain at some frequencies in either branch so that singing may occur, unless the circuit is balanced better than was required previously. For commercial telephone systems, the added gain inserted is at low and high frequencies, there being a loss over some intermediate range. As repeater circuits are more likely to be unstable at the higher frequencies singing may occur if high net gain is obtained at these frequencies, unless a voice operated device is used for changing from one-way to two-way transmission and vice versa; (3) A compromise between R_1 and R_2 , that is, a receiving end equalizer of the R_3 may be used. For example, the added gain in the lower frequency range can be retained and some of that at the lower end of the high frequency range also, thereby improving the air-to-air characteristic and at the same time not changing the circuit so much that singing will result.

III. Two-way transmission circuit, Fig. 10.—For two-way transmission over a two-wire circuit the system of Fig. 10 should be used. If two-way amplifiers are used at each end of the exposure, equalization can be made at them. It may be that no added gain can be permitted at any frequency, in which case as in the four-wire circuit discussed, R_1 would cause singing, R_2 would not and a compromise R_3 could be found that would give a part of the advantage of R_1 without its singing limitation. If no repeater is used in the circuit then perhaps some extra gain can be had without singing, permitting a better R_3 type of equalizer.

IV. Universal equalizer, Fig. 11.—In some cases it is desirable to use the same equalizer for transmission in both directions. The transmitting end equalizer and receiving end equalizer for the case of flat upper limitations on the energy and flat air-to-air characteristic differ very little for typical commercial telephone circuits and the average of the two characteristics may be taken as a universal characteristic for use whether sending or receiving. The circuit that should then be used is shown in Fig. 11 wherein the equalizers are designated SR.

What is claimed is:

1. A signal transmission system comprising two portions related in that one is subject to interfering waves whose interfering effect can be decreased by increasing the levels at which the signaling power is impressed on the system whereas the other produces interference power which increases with the increase of signal power levels, and means for impressing the signals on the system at such power levels that the interference effect produced by said interference power is substantially equal to the interference effect produced by said interfering waves and that the total interference contributed by each frequency

band of any given small width in the utilized frequency range is the same.

2. A system for transmitting signaling waves lying in a given frequency range through a region of interference, said system comprising means for so distorting the signaling waves before they reach the region of interference that, for the signaling waves in said frequency range, the average energies at the different frequencies are substantially different but contribute predetermined equal amounts to signal degradation resulting from the greatness of the magnitudes of those energies.

3. A two-way telephone transmission system for which the optimum values for the energy of the components of different frequencies in speech waves at a point in said system are substantially equal for the frequency range to be transmitted, said system comprising a telephone transmitting and receiving set having a higher transmitting efficiency for some frequencies of said range than for other frequencies of said range and having a higher receiving efficiency for some frequencies of said range than for other frequencies of said range, a common sending and receiving network fed from and feeding said set, said network having its transmission efficiency so varying with frequencies as to produce approximately said optimum relation and to effect such compensation for the variation of transmission efficiency of the other parts of the system with frequency as to render the overall transmission efficiency of the system the same for the frequencies to be transmitted.

In witness whereof, I hereunto subscribe my name this 5th day of July, 1930.

HOMER W. DUDLEY.