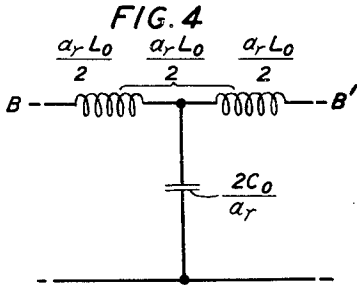
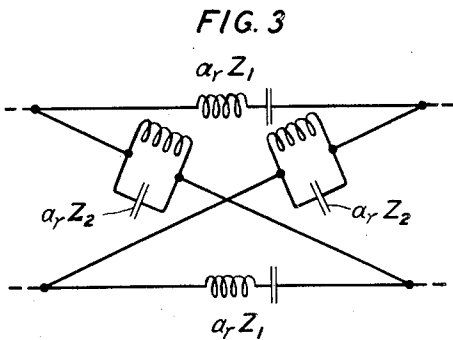
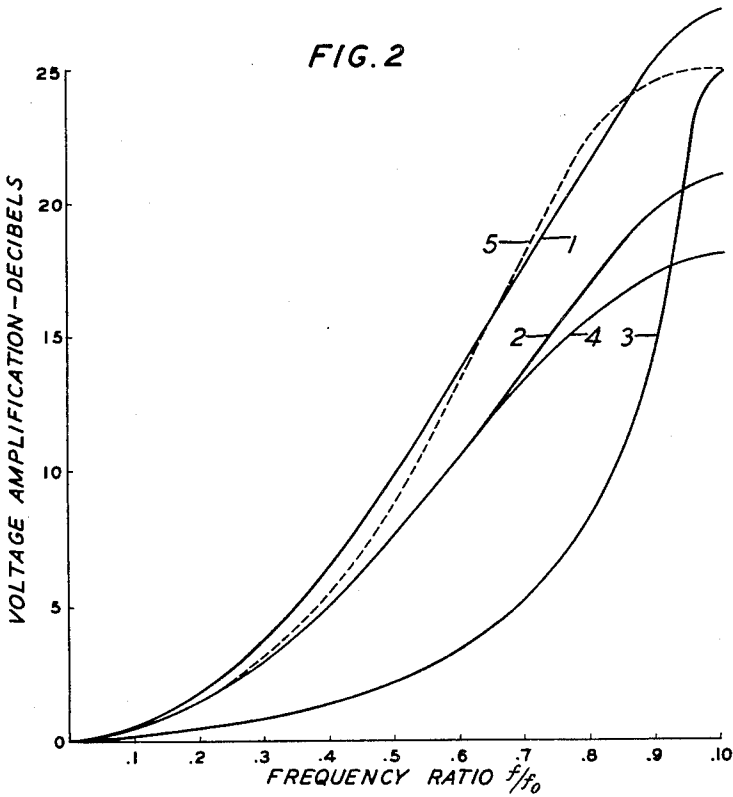
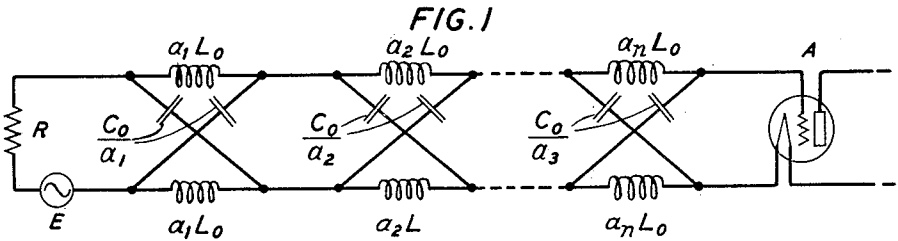


April 3, 1934.

W. R. BENNETT
TRANSMISSION NETWORK

1,953,459

Filed July 25, 1931



INVENTOR
W. R. BENNETT
BY
G. H. Stevenson
ATTORNEY

UNITED STATES PATENT OFFICE

1,953,459

TRANSMISSION NETWORK

William E. Bennett, Jersey City, N. J., assignor
to Bell Telephone Laboratories, Incorporated,
New York, N. Y., a corporation of New York

Application July 25, 1931, Serial No. 553,095

5 Claims. (Cl. 178—44)

This invention relates to wave transmission networks and more particularly to transmission equalizing networks for use in connection with very long transmission lines such, for example, as a trans-oceanic telephone cable. It has for its principal object improving the signal to noise ratio of currents received over transmission lines of this type.

In very long telephone circuits, in which for physical or other reasons repeaters cannot be used, the speech currents suffer an extremely great attenuation and, even with large input power, are received at a very low intensity at the output end. The attenuation moreover is not uniform but increases with frequency so that a large degree of amplitude distortion results.

At the receiving end of such a circuit the problems of equalization and amplification present great difficulties. If energy amplification is provided sufficient to bring the greatly attenuated high frequencies up to a suitable level, the lower frequencies, being much less attenuated in the cable, are increased so greatly in magnitude as to cause overloading of the amplifier and resulting distortion of speech. Moreover, since a large number of stages of amplification may be necessary to increase the high frequency components to the desired level, tube noises are introduced which may be sufficient to mask these frequencies. Preliminary equalization by attenuating the low frequencies to the same degree as the high frequencies serves to prevent overloading, but brings all of the signal components down to a level comparable with that of tube noises. Moreover, the use of resistive equalizers for this purpose introduces a further noise component due to the thermal agitation of the electrons in the resistance elements and still further reduces the signal to noise ratio of the received currents.

It has been found that the use in combination with a voltage responsive amplifier of a preliminary equalizer containing only reactance elements permits the voltages of the higher frequency signal components to be increased without affecting the initial signal to noise ratio. The number of amplifier stages required for the subsequent amplification of the signal is also diminished and the tube noises are correspondingly reduced. This method of equalization depends primarily on resonance effects in the reactive equalizer whereby the voltages of the higher frequency signal components are selectively increased. To make use of it in cases where a large degree of equalization is needed over a wide range of frequencies a problem presents itself

due to the sharply selective character of resonant circuits. It is possible with simple resonant circuits to obtain very high amplification of a single frequency or of a group in a narrow frequency range, but frequencies outside this range may be amplified so little that no useful equalization results. Ordinary combinations of resonant circuits tend to produce multiple resonance peaks in the equalization characteristic which are detrimental to the transmission.

In accordance with this invention a reactance type equalizer is provided which provides a high degree of amplification of the high frequency signal currents together with a proportionately large amplification of the lower frequency currents. In its general form the equalizer of the invention comprises a plurality of reactive networks coupled together in tandem to form a tapered artificial line. In the preferred form each section of the equalizer is an all-pass network and all sections have the same propagation constants but different characteristic impedances, the latter increasing in value in a prescribed manner from one end of the line to the other. The equalization characteristic may be regarded as being due to the summation of the reflection effects at the junctions of the sections and at the ends of the line and may be modified by varying the characteristic impedances of the component sections.

The invention will be more fully understood from the following detailed description and by reference to the drawing of which

Fig. 1 illustrates schematically a network in accordance with the invention;

Fig. 2 shows curves illustrating typical characteristics of the network of Fig. 1; and

Figs. 3 and 4 illustrate alternative forms of the networks of the invention.

The equalizer shown in Fig. 1 comprises n sections of all-pass lattice networks in which the line impedances are inductances and the lattice impedances are simple capacities. At one end the network is connected through a resistance R to a source of oscillations having an E. M. F. E , this combination representing a cable or long transmission line with which the equalizer is to be used. At the other end the network terminals are connected directly to the grid and cathode respectively of an amplifier A which may be the first stage of a multi-stage receiving amplifier. The amplifier A provides a virtual open circuit termination for the network.

Taken in their order from the input end of the

line, the inductances of the lattice sections have the respective values:

$$a_1 L_0, a_2 L_0, \dots, a_n L_0, \quad (1)$$

and the capacities have the values

$$\frac{C_0}{a_1}, \frac{C_0}{a_2}, \dots, \frac{C_0}{a_n} \quad (2)$$

where the a 's represent numerical coefficients.

From the well known formulæ relating to lattice networks it follows that the characteristic impedance and the propagation constant of the r -th section are given by

$$Kr = a_r \sqrt{\frac{L_0}{C_0}} \quad (3)$$

and

$$\tanh \frac{P}{2} = j 2 \pi f \sqrt{L_0 C_0} \quad (4)$$

where K and P denote respectively the characteristic impedance and the propagation constant, and f denotes frequency. The characteristic impedance is constant and resistive, the value being proportional to the numerical coefficient a_r . The propagation constant is evidently the same for all sections and is a pure imaginary quantity. This corresponds to the fact that the attenuation constant, which is defined as the real part of the propagation constant, is zero at all frequencies. Networks of this type are adapted to transmit currents of all frequencies substantially without attenuation and have been termed all-pass networks. The general type of four-terminal reactance network has a propagation constant which is real in certain frequency ranges and imaginary in others, the real values occurring in attenuation ranges and the imaginary values in ranges of free transmission. If L_0 and C_0 are so chosen that

$$\sqrt{\frac{L_0}{C_0}} = R$$

and if the resonance frequency indicated by the product $L_0 C_0$ be denoted by f_0 , Equations (3) and (4) become

$$Kr = a_r R \quad (5)$$

and

$$\tanh \frac{P}{2} = j \frac{f}{f_0} \quad (6)$$

If the a coefficients were all unity the network characteristic impedance would be equal to the resistance R of the connected line and as a result of this impedance match waves of all frequencies would be transmitted to the amplifier without change of amplitude. To provide a variable amplification of the output E. M. F. the a coefficients of the successive sections taken in order from the input end are given increasing values so that the characteristics impedances of the several sections increase progressively towards the amplifier terminals. A wide variety of voltage characteristics is obtainable by appropriate selection of the impedance values, but it has been found that the most satisfactory characteristics for the purpose of equalizing the attenuation in long telephone cables are obtained by stepping up the characteristic impedances only a small amount in the sections at the input end and rapidly increasing the step-up ratio in the successive sections. By this arrangement it is possible to obtain a voltage amplification which, measured in decibels, increases in a nearly linear fashion with

frequency in a preassigned range and which therefore is well adapted to compensate the attenuation variation in a long line.

It has been possible to determine by calculation the values of the characteristic impedances required to give voltage amplification characteristics conforming to certain general formulæ which represent useful types of variation. For example, if the desired variation of the voltage ratio be expressed by the formula

$$\left| \frac{E_2}{E} \right|^2 = \frac{\left(1 + \left(\frac{f}{f_0} \right)^2 \right)^{2n}}{1 + \left(\frac{f}{f_0} \right)^{4n}} \quad (7)$$

where E_2 denotes the output voltage, E the line voltage, and n the number of sections in the equalizer, the values of the a coefficients determining the characteristic impedances are found to be as indicated by the following table:

No. of sections	a_1	a_2	a_3	a_4	a_5
1.....	1.414				
2.....	1.036	2.93			
3.....	1.004	1.248	7.036		
4.....	1.0004	1.041	1.810	19.68	
5.....	1.00003	1.002	1.20	3.0	45

The form of the voltage characteristic is shown by curves 1 and 2 of Fig. 2 in which the abscissæ are proportional to the frequency and the ordinates to the logarithm of the voltage ratio E_2/E . Curve 1 corresponds to an equalizer of five sections and curve 2 to one having four sections. For comparison, curve 3 shows the voltage ratio variation obtainable with a single resonant circuit proportioned to give a maximum gain of 25 decibels.

The method of calculating the coefficients in the above case depends upon the fact that the voltage ratio in the general case can be expressed in the form

$$\frac{E_2}{E_1} = \frac{(1 - X^2)^{2n}}{N_{2n}}$$

where

$$X = j \frac{f}{f_0}$$

and N_{2n} is a polynomial in X of degree $2n$, the coefficients of the terms of which are functions of the a coefficients of the several network sections. By identifying the absolute value of the square of the polynomial N_{2n} with the expression

$$1 + |X|^{4n}$$

in accordance with the procedure discussed in my copending application Serial No. 374,669, filed June 29, 1929, a set of equations can be obtained which are sufficient for the determination of the impedance coefficients.

It will be noticed that where the number of sections exceeds two, the characteristic impedance of the first few sections is practically the same as the line impedance R , the a coefficients being very close to unity. Since the impedance mismatching at the junctions of the initial sections is in these cases so slight it is evident that only slight modification of the characteristics would result from their omission. For practical purposes the network need not generally

include more than three sections although when large gains are desired these may be designed on the basis of a greater number of sections.

Another form of the voltage ratio variation for which the a coefficients can be calculated is

$$\left| \frac{E_2}{E_1} \right| = \frac{\left(1 + \left(\frac{f}{f_0} \right)^2 \right)^n}{1 + \left(\frac{f}{f_0} \right)^{2n}} \quad (8)$$

the method of calculation in this case following along lines similar to those indicated above. The values of the a coefficients for numbers of sections up to four are given in the table below.

No. of sections	a_1	a_2	a_3	a_4
1-----	1			
2-----	1.061	2.121		
3-----	1	1.25	5	
4-----	1.001	1.036	1.738	13.51

The single-section network in this case gives no voltage amplification and therefore is not of interest. Likewise in the three-section network the first section may obviously be omitted.

The voltage amplification obtained by a four-section network of this type is indicated by curve 4 of Fig. 2. In the lower frequency range the characteristic is about the same as that of the four-section network corresponding to curve 2, but at higher frequencies the slope of the characteristic is more gradual and the maximum gain is less. The gain at intermediate frequencies is higher in proportion to the maximum gain than in the case of curve 2.

While the proportions given in the foregoing tables provide highly desirable characteristics, other proportions may also be used and useful characteristics may be obtained therewith. Dotted curve 5 of Fig. 2 represents the voltage amplification characteristic of a two-section network for which $a_1=3.07$ and $a_2=17.8$. For a large part of the frequency range the amplification is not greatly different from that of the five-section network corresponding to curve 1, although the variation is somewhat less regular. By following the plan of increasing the impedance mismatch at the successive junction points the general form of the characteristic is maintained and by varying the degree of mismatching at the different junction points the shape of the characteristics may be varied to a large extent.

Networks of the type shown in Fig. 1 are characterized by a voltage amplification characteristic having a single maximum occurring at the resonance frequency f_0 . By the use of more complex impedances in the branch arms, characteristics having more than one maximum can be obtained. For example, if each section consists of an all-pass network of the type shown in Fig. 3, a characteristic having two maxima is obtained. In this network the line and the lattice impedances of the r^{th} section are designated $a_r Z_1$ and $a_r Z_2$ respectively, Z_1 and Z_2 being series resonant and parallel resonant circuits respectively, tuned to the same frequency and proportioned reciprocally so that

$$Z_1 Z_2 = R^2$$

The voltage characteristic of this type of network can be made to follow variations represented

by formulæ similar to Equations (7) and (8), namely

$$\left| \frac{E_2}{E_1} \right| = \frac{(1 + |X|^2)^{2n}}{1 + |X|^{4n}} \quad (9)$$

and

$$\left| \frac{E_2}{E_1} \right| = \frac{(1 + |X|^2)^n}{1 + |X|^{2n}} \quad (10)$$

if the a coefficients are given the values in the tables above corresponding to Equations (7) and (8) respectively. The function X in this case has the form

$$X = j \frac{f - \frac{f_1 f_2}{f}}{f_1 - f_2} \quad (11)$$

where f_1 and f_2 are the two resonance frequencies of the impedance constituted by a line branch and a lattice branch in series. Since X is unity at each of these frequencies they correspond to maxima in the voltage characteristic.

The lattice type networks of Figs. 1 and 3 being of the balanced type are not well adapted for use in systems having one side of the line grounded. In such systems the balanced lattices may be replaced by their unbalanced equivalents, for example, the lattices of the network of Fig. 1 may be replaced by networks of the type shown in Fig. 4. In this network, which corresponds to the r^{th} section of Fig. 1 there are included in one side of the line two inductances each equal to

$$\frac{a_r L_0}{2}$$

which are coupled together with unity coupling in series aiding relation from terminal B to terminal B'. At the mid-point a capacity

$$\frac{2 C_0}{a_r}$$

is connected across the line.

Other types of unbalanced equivalents of a lattice which may be used in place of the network of Fig. 3 are shown in United States patent to H. Nyquist 1,770,422, issued July 15, 1930.

In the appended claims the term "all-pass network" is used to define a four-terminal reactance network having an attenuation constant which is substantially zero at all frequencies.

What is claimed is:

1. A frequency selective transmission network adapted to operate between a wave source having relatively low impedance and a receiving device having a high input impedance comprising a plurality of all-pass reactance networks connected in tandem, said reactance networks having the same propagation constants and having characteristic impedances which increase in value progressively from one end of the transmission network to the other.

2. A frequency selective transmission network adapted to operate between a wave source and a receiving device having a very high input impedance comprising a plurality of all-pass reactance networks connected in tandem, said reactance networks having the same propagation constants and having characteristic impedances which increase in value progressively and at an increasing rate from one end of the transmission network to the other.

3. A frequency selective transmission network adapted to operate between a wave source of relatively low impedance and a receiving device of very high impedance comprising a plurality of all-pass reactance networks connected in tandem, said reactance networks having character-

istic impedances which increase in value progressively from one end of the network to the other and having equal propagation constants, the propagation constant and the relative values of

5 the characteristic impedances being proportioned to provide a voltage transfer characteristic which increases approximately uniformly throughout a preassigned frequency range.

4. In combination, a wave source of relatively
10 low impedance, a receiving amplifier having a very high input impedance and a transmission network coupling said source to the input terminals of said amplifier, said transmission network comprising a plurality of all-pass reactance networks
15 connected in tandem having equal propagation constants and having characteristic impedances which increase progressively in value from stage to stage towards the end of the transmission net-

work connected to the amplifier whereby a voltage transfer characteristic is obtained which increases progressively over a wide range of frequencies.

5. In combination, a long telephone line, a receiving amplifier therefor, and a transmission network coupling said line to the input terminals of said amplifier, said network comprising a plurality of sections each of which is an all-pass reactance network having a constant resistance
85 characteristic impedance, and said sections being proportioned to have characteristic impedances which increase progressively from section to section towards the receiving amplifier whereby the network has a voltage amplification characteristic adapted to compensate the attenuation of
90 the telephone line in the speech range.

WILLIAM R. BENNETT.

20	95
25	100
30	105
35	110
40	115
45	120
50	125
55	130
60	135
65	140
70	145
75	150