March 4, 1930. H. NYQUIST ET AL 1,749,045

SIGNALING SYSTEM

Filed June 11, 1927

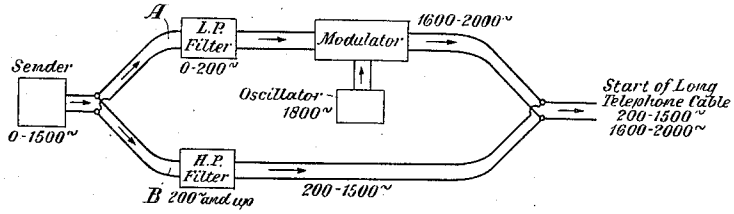


Fig. 1

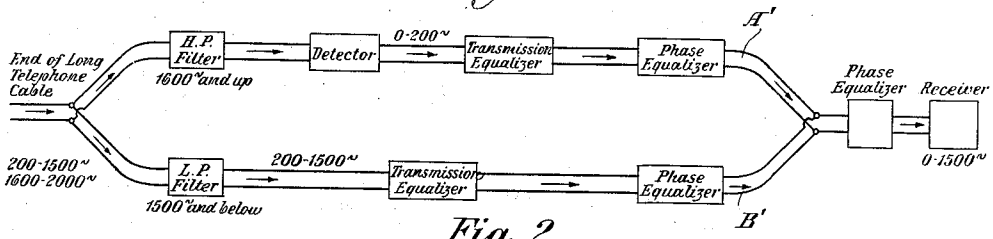


Fig. 2

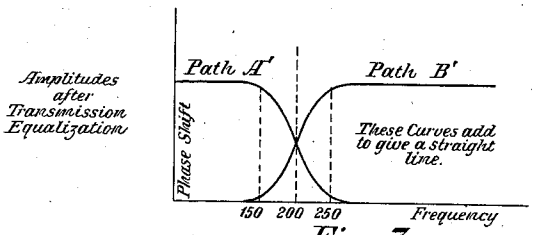


Fig. 3

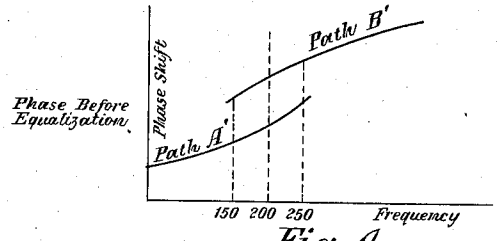


Fig. 4

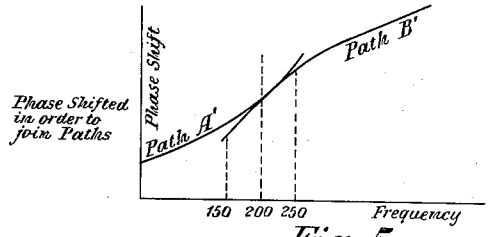


Fig. 5

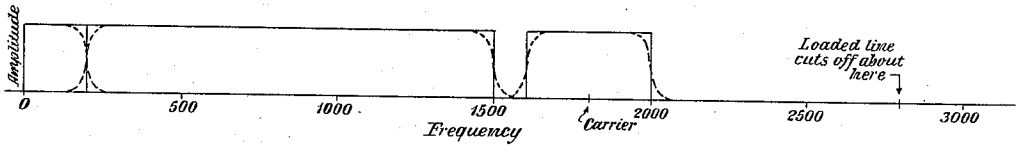


Fig. 6

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Patented Mar. 4, 1930 1,749,045

UNITED STATES PATENT OFFICE

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SIGNALING SYSTEM

Application filed June 11, 1927. Serial No. 198,285.

It is an object of our invention to provide for effectively transmitting a composite current comprising component currents of frequencies in a band from zero up to a considerable value. Another object of our invention is effectively to transmit the lower end part of such a band of frequencies by cutting it off and stepping it up in frequency above the upper end of the band for actual transmission. Other objects of our invention have to do with carrying out this procedure without distortion either in respect to amplitude or phase shift. Another object of our inventon is effectively to transmit at high speed signal currents comprising components of a wide range of frequencies from zero up to a certain limiting value. Another object is to effect such transmission over a line which will actually transmit only from a frequency somewhat above zero to a frequency somewhat above said limiting value. Still another object of our invention is to separate the components of a signal into separate channels according to their frequency above and below a certain critical intermediate frequency, and then to recombine them with proper attenuation equalization and phase correction so that as recombined the resultant signal wave will correspond accurately with the initial signal wave. All these objects and other objects of our invention will be made apparent in the following specification and claims taken with the accompanying drawings, in which we have disclosed an example of the practice of our invention. It will be understood that this disclosure is specific to this example, and that the scope of the invention is intended to be indicated in the appended clams.

In the drawings, Figure 1 is a diagram of apparatus at the transmitting end of a signaling system; Fig. 2 is a diagram of apparatus at the receiving end; and Figs. 3 to 6 are coordinate diagrams of amplitude and phase shift as functions of frequency.

To illustrate our invention, it will be shown how an increase in speed of telegraph transmission may be obtained over a telephone line whose band of transmitted frequencies is limited. This invention is applicable to any high-speed D. C. telegraph system where it is desired to transmit only a portion of the component frequencies by means of a carrier wave.

Some forms of high-speed telegraphy are now accomplished by transmitting sudden spurts of carrier current occurring so rapidly that a band of frequencies about 400 cycles wide is required on each side of the carrier frequency for their transmission, making a total transmitted band of 800 cycles in width. If the speed is doubled, then a line would be required which transmits twice that band, or 1,600 cycles. If the speed is again doubled, a line would be required which transmits twice 1,600. or 3,200 cycles. This assumes, of course, that sending and receiving mechanisms can be devised to operate at these speeds. The latter speed cannot be handled by medium-heavy loaded circuits since they cut off at about 2,800 cycles. Neither is it possible to transmit the envelope of the carrier wave as a series of D. C. pulses ranging in frequency components from zero to 1,600 cycles because the line and apparatus do not transmit the very low frequencies. But it is possible to obtain this highest speed with such a line when the very low-frequency components are separated from the rest of the signal and transmitted by carrier waves.

Figs. 1 and 2 show an application of this method to the transmission of a signal including frequencies from zero to 1,500 cycles. This range is indicated in Fig. 6. It is assumed that the cable does not transmit frequencies much below 200 cycles. The filters located at A and B in Fig. 1 divide the original signal into two paths, one transmitting from zero to about 200 cycles and the other from about 200 to 1,500 cycles. The currents of the path A are too low in frequency to be transmitted over the cable and consequently are used to modulate an 1,800-cycle carrier wave, the products of modulation being about 1,600 to 2,000 cycles, which are easily transmitted by the cable. The currents from the two paths are combined and transmitted over the cable, the frequencies ranging from 200 to 2,000 cycles.

A carrier wave of 1,800 cycles is used in-

stead of 1,700 cycles (which would give products of modulation from 1,500 to 1,900 cycles) in order to allow for the fact that the filters cannot be made to cut off sharply and to avoid overlapping of the lower side band with the frequencies below 1,500 cycles. This is made apparent in Fig. 6.

At the receiving end of the line the filters in paths A′ and B′ in Fig. 2 separate the products of modulation from the other frequencies. The former pass through a detector and reappear at the output as currents of zero to 200 cycles. Transmission equalizers are shown in order to adjust the amplitudes of the currents of each path to the proper values so that on combining them the original signal will be exactly reproduced, provided the currents are all in the correct phase relation. The details of construction of transmission equalizers, phase equalizers, and filters are well known and therefore they will not be given here.

The correct phase relation for distortionless transmission is obtained by means of phase equalizers which may be separate from the transmission equalizing networks. Such phase equalizers may consist of lattice type all-pass networks or their equivalent. Due to the fact that the filters used in Fig. 1 do not cut off sharply at 200 cycles it will be found that in the path A′ of Fig. 2, currents will exist of frequencies slightly greater than 200 cycles, while in path B′ there will be some frequencies less than 200 cycles. It is necessary that the phases of currents in this overlapping portion of the frequency band be so adjusted that where paths A′ and B′ join, the currents will not cancel due to being in phase opposition. In choosing the transmission and phase equalizers of Fig. 2, it is necessary to know what phase displacement and amplitude each current in path A′ has at the output of the detector and likewise in path B′ at the output of the low-pass filter. This information may be obtained either by computation or by measurement after the circuit has been set up. In order that the combined currents should give the exact reproduction of the original signal it is first necessary that currents of all frequencies, 0–1,500 cycles be transmitted equally. Therefore, the transmission equalizers Nos. 1 and 2 should be arranged to correct the amplitudes according to Fig. 3 so that when currents of the two paths are combined in phase the resulting amplitude-frequency curve will be a straight line, equal to the sum of the two curves in Fig. 3.

The phase of currents in paths A′ and B′ measured before correction may be plotted as two separate curves shown in Fig. 4 which may or, most likely, may not be straight lines. Unless the curves coincide over the frequency range common to both paths or are parallel and a multiple of 360° apart then the two currents of each frequency will not add directly as desired. This may be overcome as in Fig. 5, by the use of a phase shifting network in each path so that the two curves become tangent at 200 cycles and substantially coincident throughout the frequency range common to both paths, or else the two curves may be made substantially parallel but a multiple of 360° apart throughout this range.

The system disclosed will be dependent for success on the design of these networks. Perhaps the simplest networks to construct are ladder-type filters. One or more sections of simple low pass filter, with series inductance and shunt capacity, may be used for the phase equalizer of path A′ in Fig. 2. The phase shift per section in the non-attenuation range, is given by the formula:

$$\beta = 2 \sin^{-1} \frac{f}{f_c}$$

where f_c = cut-off frequency of the filter. The phase shift is zero at zero frequency and increases faster and faster with increase in frequency up to the cut-off point. By locating f_c above 250 cycles the desired phase shift may be obtained (concave upward) which, added to the curve for path A′ of Fig. 4, gives the curve for path A′ of Fig. 5. The number of sections and the location of f_c for each section is an adjustment to be determined by the designer of a particular installation. For example, by raising f_c, the curve can be made less concave, while by increasing the number of sections the curve can be made steeper, and the total phase shift increased. In calculating the total phase shift caused by a number of sections of filter it is, of course, necessary, for accurate results, to take account of the impedances connected to the filter.

The phase equalizer of path B′ in Fig. 2 may consist of one or more sections of simple high pass filter, with series capacity and shunt inductance. The phase shift per section in the non-attenuating range is given by the formula:

$$\beta = -2 \sin^{-1} \frac{f_c}{f}$$

The phase shift is zero at infinite frequency and increases negatively with decrease in frequency down to the cut-off point. By locating f_c below 150 cycles, the desired phase shift may be obtained (concave downward) which, when added to the curve for path B′ of Fig. 4 gives the curve for path B′ of Fig. 5. The exact number of sections and the location of the respective cut-off frequencies is determined by the designer for each installation just as in the case of the low pass filters. It is also possible to accomplish the desired result by the use of lattice-type all-pass networks or their equivalent

which have the advantage of possessing a constant characteristic impedance at all frequencies, which simplifies the calculations when they are terminated in matched impedances. In this case it is only necessary to consider the equation of each section which gives the phase shift:

$$\beta = 2\tan^{-1}\frac{b}{2}\left(\frac{f}{f_o}-\frac{f_o}{f}\right)$$

In this equation, b and f_o are arbitrary constants which may be chosen at will and from which the constants of the network may be computed by methods well known to those skilled in the art. The phase shift caused by this network is $-180°$ at zero frequency, zero at the frequency $f=f_o$ and $+180°$ at infinite frequency. The slope of the curve at various points is governed by b. The designer may take one or more of these networks in path A′, and choose f_o below 200 cycles, while other networks may be placed in path B′ with their f_o above 200 cycles. By taking the right number of sections and adjusting the constant b of each network, the slopes of the resulting phase curves for each path may be varied until they come tangent or meet the specifications outlined above for proper joining of the paths. In order to obtain a 180° phase shift whenever necessary the connections to one of the paths may be reversed. For accurate work it is necessary, of course, that the phase and transmission equalizers be designed to allow for the fact that in practical construction the former will have some effect on the attenuation and the latter some effect on the phase.

The combined currents at the junction of paths A′ and B′ will then have the desired amplitude characteristic but probably a somewhat irregular delay curve. The phase equalizer directly on the input side of the receiver in Fig. 2, consisting of lattice-type networks, may be employed in the customary manner, to give a flat delay curve to currents entering the receiving device. When all frequencies are transmitted with substantially equal amplitudes and delay, the signals are practically free from distortion.

We claim:

1. The method of transmitting a signal, which consists in separating its components into respective channels approximately above and below a certain critical frequency, equalizing the attenuation and equalizing the phase shift in these channels to offset departures occasioned by said separation, and then recombining the components to produce a resultant signal like the initial signal.

2. The method of compensating for the departure from exact cut-off given by filters when separating components of a signal wave in separate channels according to frequency; which consists in equalizing the attenuation and phase shift in the separate channels and thereafter combining the currents in those channels.

3. In combination, a channel, branches therefrom, means to effect an approximate separation of the components of a signal current wave from said channel into said branches according to frequency, means in said branches to compensate for attenuation and phase shift, and means to combine the components in the branches whereby the resultant current will have the same signal form as the initial current.

4. The method of separating components of a signal current according to frequency and recombining them, which consists in filtering such components apart with so much distortion at frequencies near the separation frequency as may be unavoidable, and then compensating the separated current components for attenuation and phase shift so that when recombined the resultant current will correspond to the initial current.

5. In the method of combining currents of adjacent frequency ranges with slight overlap, the step which consists in compensating them for attenuation and phase shift at frequencies which overlap, so that when they are combined there will be no irregularity of amplitude nor of phase shift at those frequencies.

6. In combination, a line good for transmitting currents of frequencies only from a to d, means at the sending end to generate signal currents with components at frequencies from 0 to b, means to separate these into two channels with ranges from 0 to a and from a to b, means to generate a carrier at c and modulate it by the said lower range, thus producing a modulated output of range within $c-a$ to $c+a$, means to apply such output and the current of range a to b to the said line, means to separate these ranges at the receiving end, a detector to get the current components from 0 to a from the higher received range, compensators for attenuation and for phase shift for the separated resultant currents, means to combine these currents after compensation, and a receiver to which such combined currents are applied, the frequency values having magnitudes in the order $0, a, b, c-a, c, c+a$ and d.

7. The method of effecting the transmission of signal currents of components from 0 to b in frequency, over a line that transmits only from a to d, which consists in separating the signal components into respective channels below and above a, stepping the lower such range up to a range lying between b and d, then transmitting both ranges on said line, and, at the receiving end, separating them and stepping the higher range down to 0 to a, compensating these separated ranges for attenuation and phase shift and combining them to produce a signal wave like the initial wave at the transmitting end,

the frequency values having magnitudes in the order 0, a, b, and d with $d-b>2a$.

8. The method of effecting transmission of signal currents of component frequencies from zero up to a considerable value over a line which will not transmit directly currents of low frequency, which consists in separating off the low frequency components, stepping them up in frequency above the upper limit of the signal frequency range, transmitting both ranges, and, at the receiving end, stepping the higher range down to the corresponding initial values, compensating in both ranges for attenuation and phase shift and combining and applying the resultant currents to produce a received signal current like the initial current at the sending end.

9. The method of transmitting a signal current comprising components of two adjacent frequency ranges which may be designated as the first range and the second range over a line capable of transmitting only frequencies within said second range and a third range, which consists in separating the first and second ranges at the sending end, shifting the said first range by modulation to within the third range, then transmitting the said last-mentioned range and the said second range, and at the receiving end, separating the second range and third range currents, stepping the third range currents down to their initial values as in the first range, and then combining the resultant currents to get a signal current corresponding to the initial signal current at the sending end.

10. In combination, means to produce a signal current having frequency components lying in two ranges which may be designated first and second, a line adapted to transmit frequency components in the second range and another range which may be designated as the third, means at the sending end to separate the components of the first and second ranges and to shift the frequency of the first range components into the third range, means to apply the currents of the second and third ranges to the line, and, at the receiving end, means to separate these ranges, means to step the currents in the third range back to the initial values of the first range, means to compensate the first range currents and the second range currents for attenuation and phase shift, and means to combine and apply the currents so compensated to produce a resultant signal wave like the initial signal wave at the sending end.

11. The method of transmitting a signal, which consists in separating its components into respective channels approximately above and below a certain critical frequency, equalizing the attenuation and equalizing the phase shift in each of these channels to offset departures occasioned by said separation, and then recombining the components to produce a resultant signal like the initial signal.

In testimony whereof, we have signed our names to this specification this 9th day of June, 1927.

HARRY NYQUIST.
KENNETH W. PFLEGER.