March 15, 1949. J. R. PIERCE 2,464,607

PULSE CODE MODULATION COMMUNICATION SYSTEM

Filed July 9, 1945 8 Sheets-Sheet 1

FIG. 1

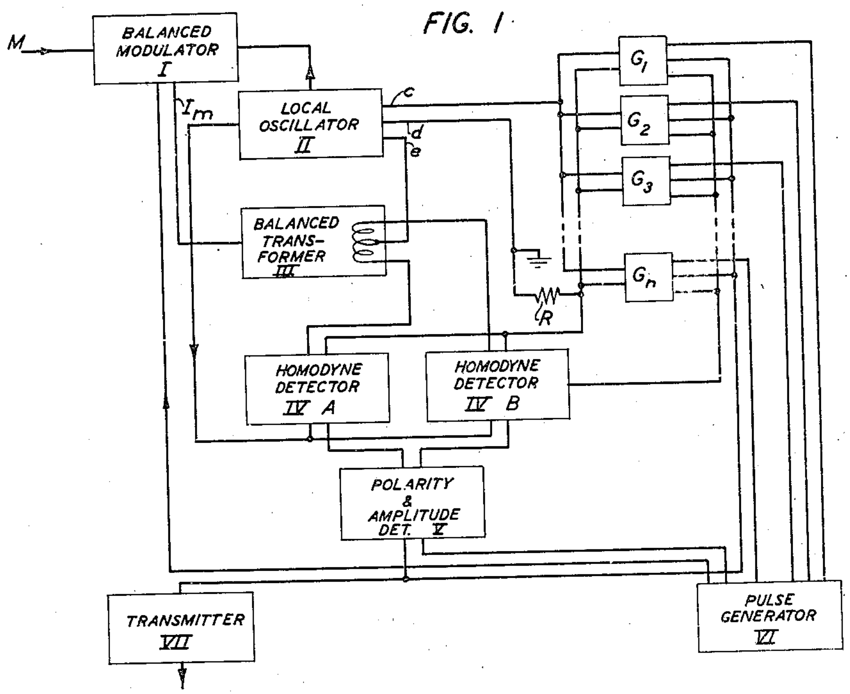

FIG. 2

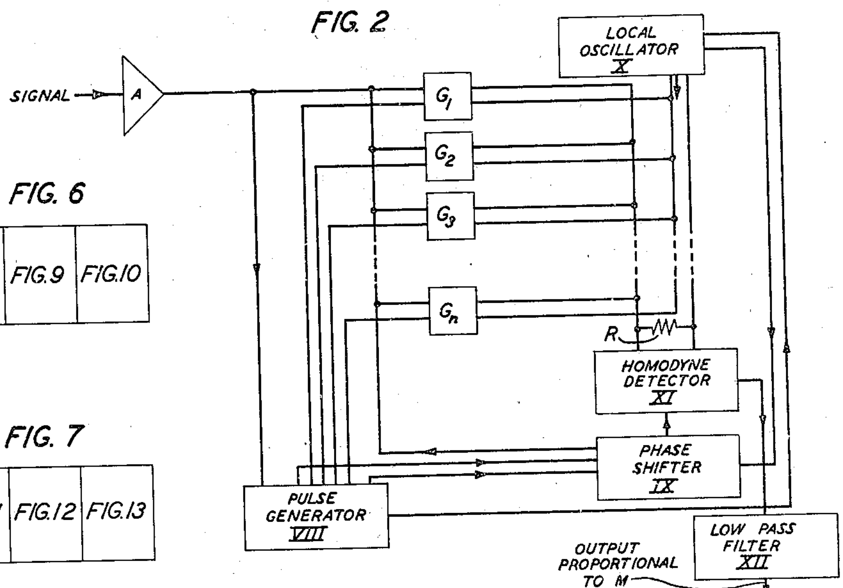

FIG. 6

FIG.8	FIG.9	FIG.10

FIG. 7

FIG.11	FIG.12	FIG.13

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PULSE CODE MODULATION COMMUNICATION SYSTEM

Filed July 9, 1945 8 Sheets-Sheet 2

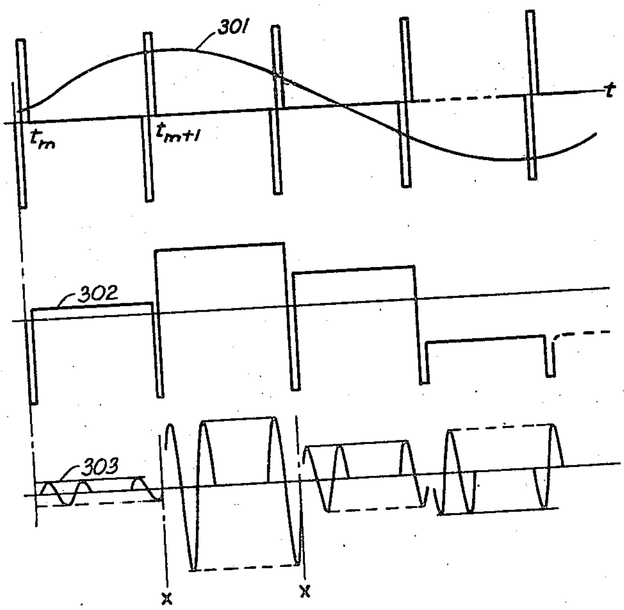

FIG. 3

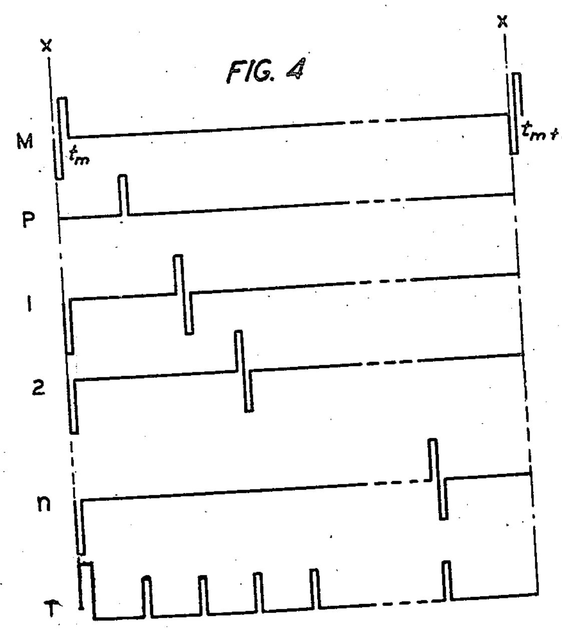

FIG. 4

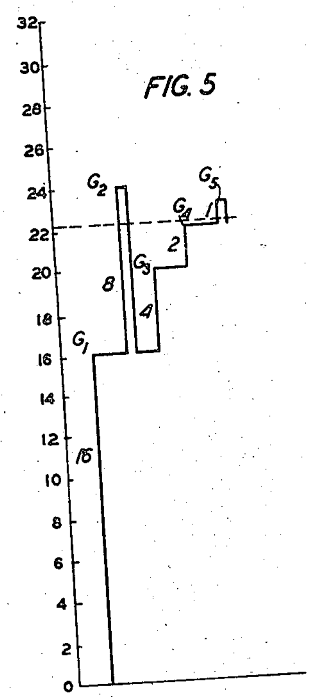

FIG. 5

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March 15, 1949. J. R. PIERCE 2,464,607

PULSE CODE MODULATION COMMUNICATION SYSTEM

Filed July 9, 1945 8 Sheets-Sheet 3

FIG. 8

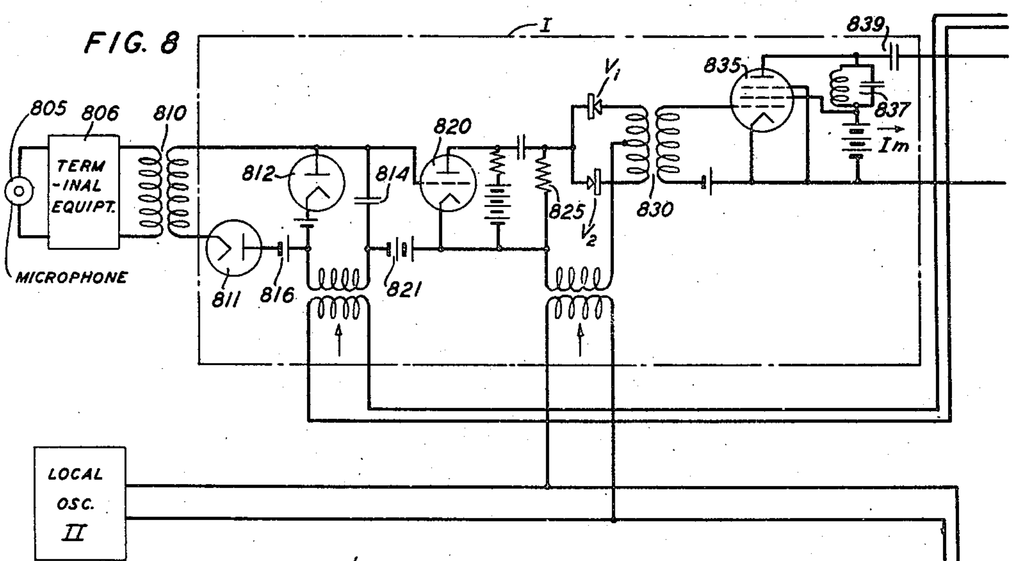
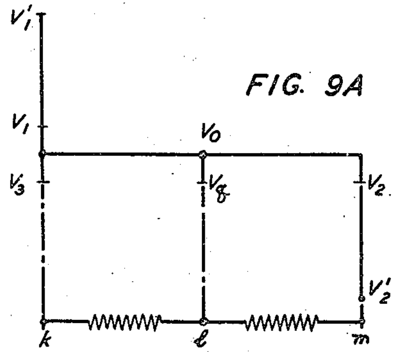
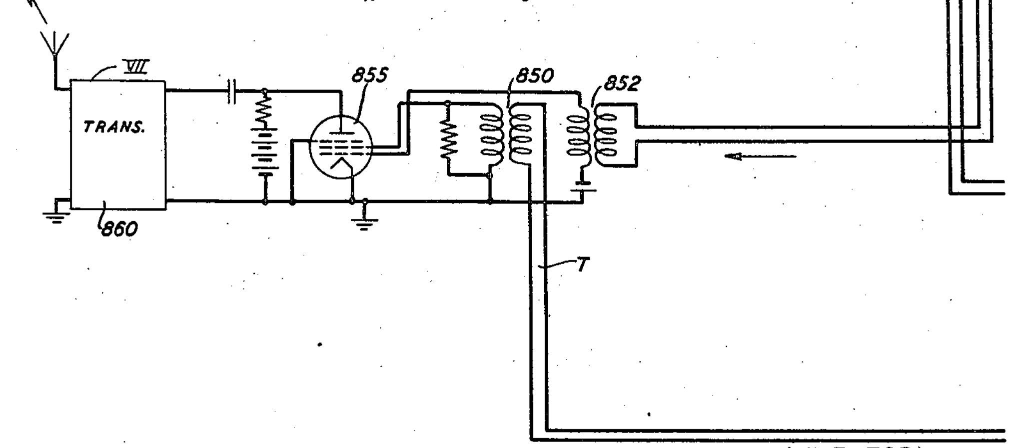


FIG. 9A





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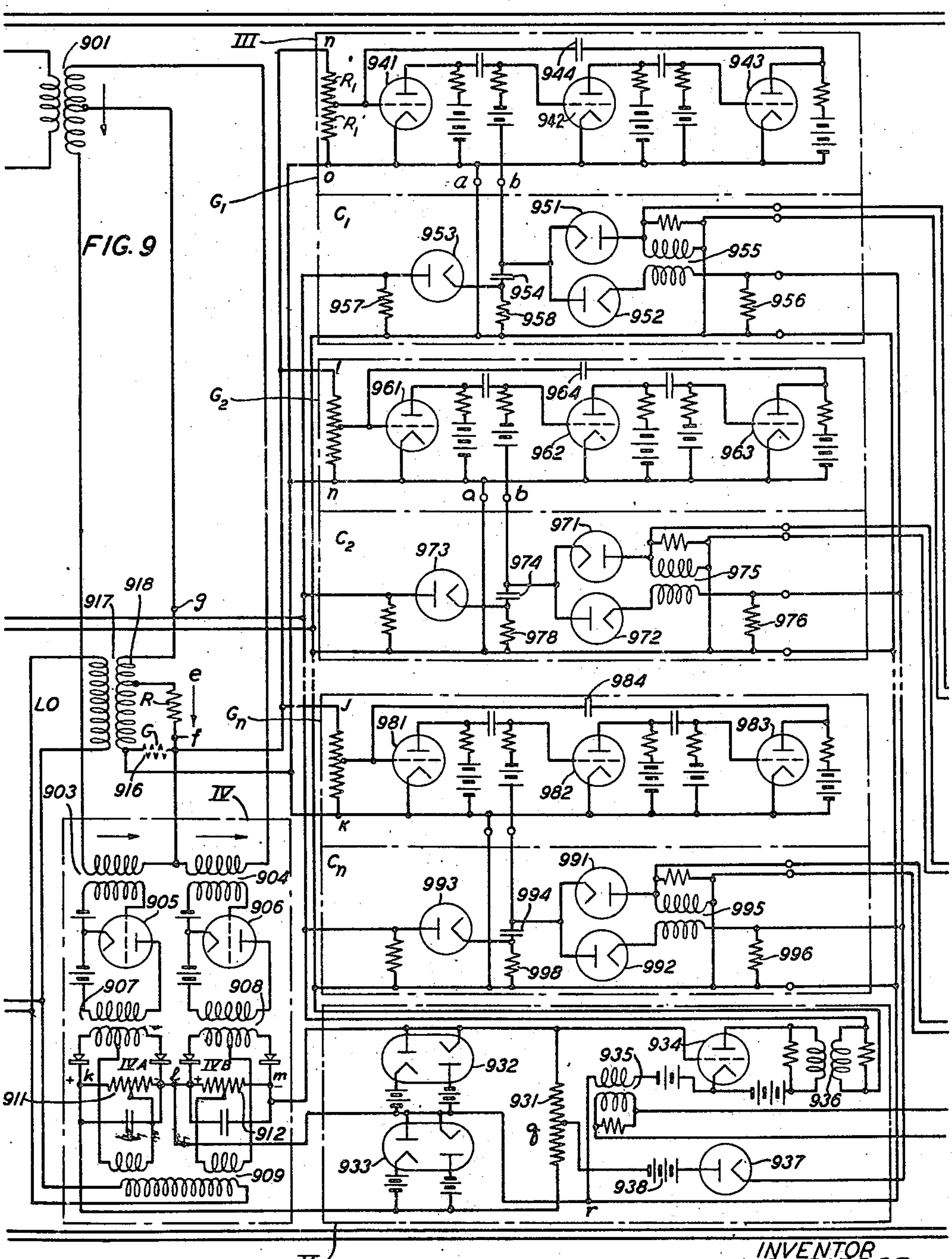
PULSE CODE MODULATION COMMUNICATION SYSTEM

Filed July 9, 1945 8 Sheets-Sheet 4



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PULSE CODE MODULATION COMMUNICATION SYSTEM

Filed July 9, 1945 8 Sheets-Sheet 5

FIG. 10

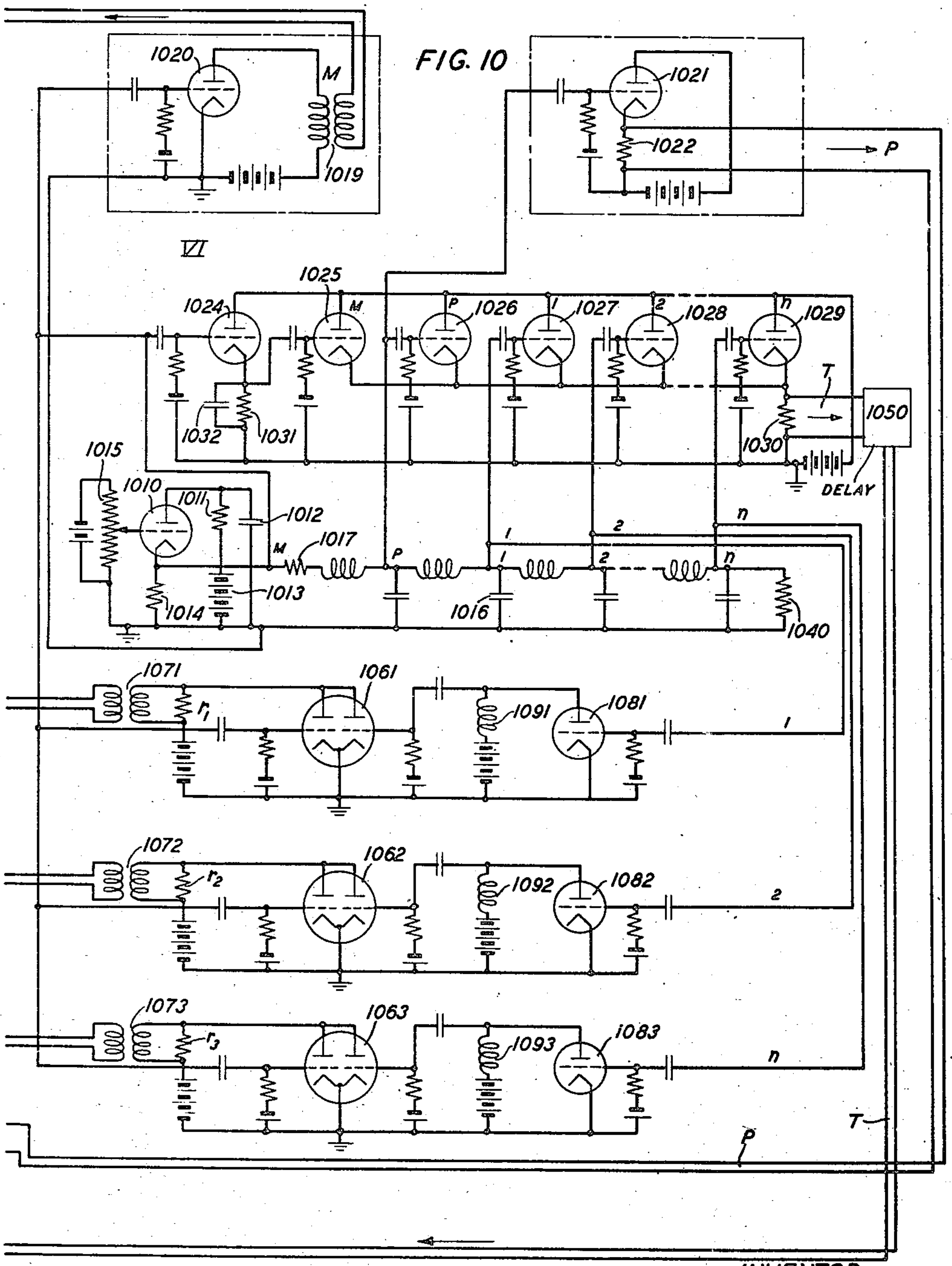

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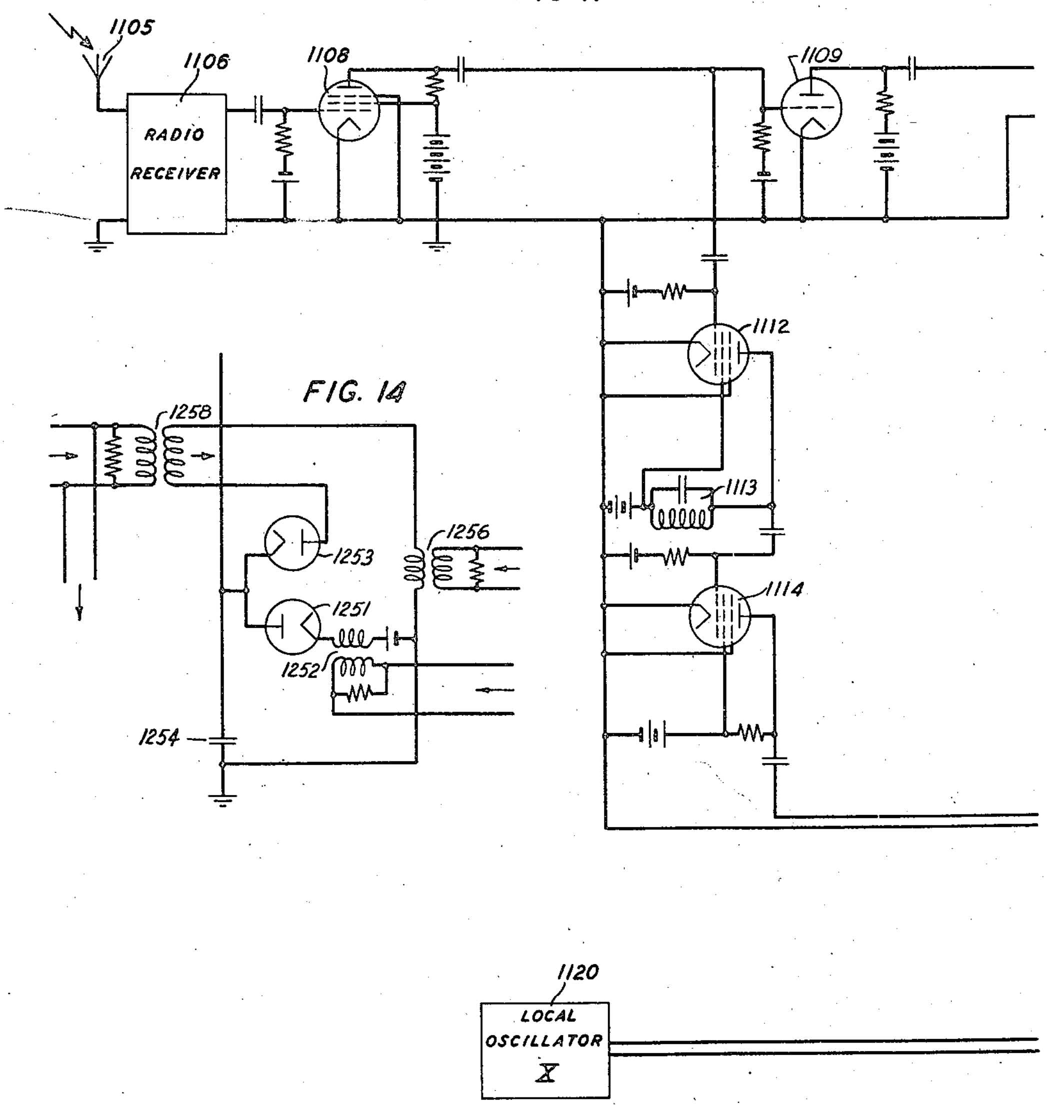
FIG. 11

FIG. 14



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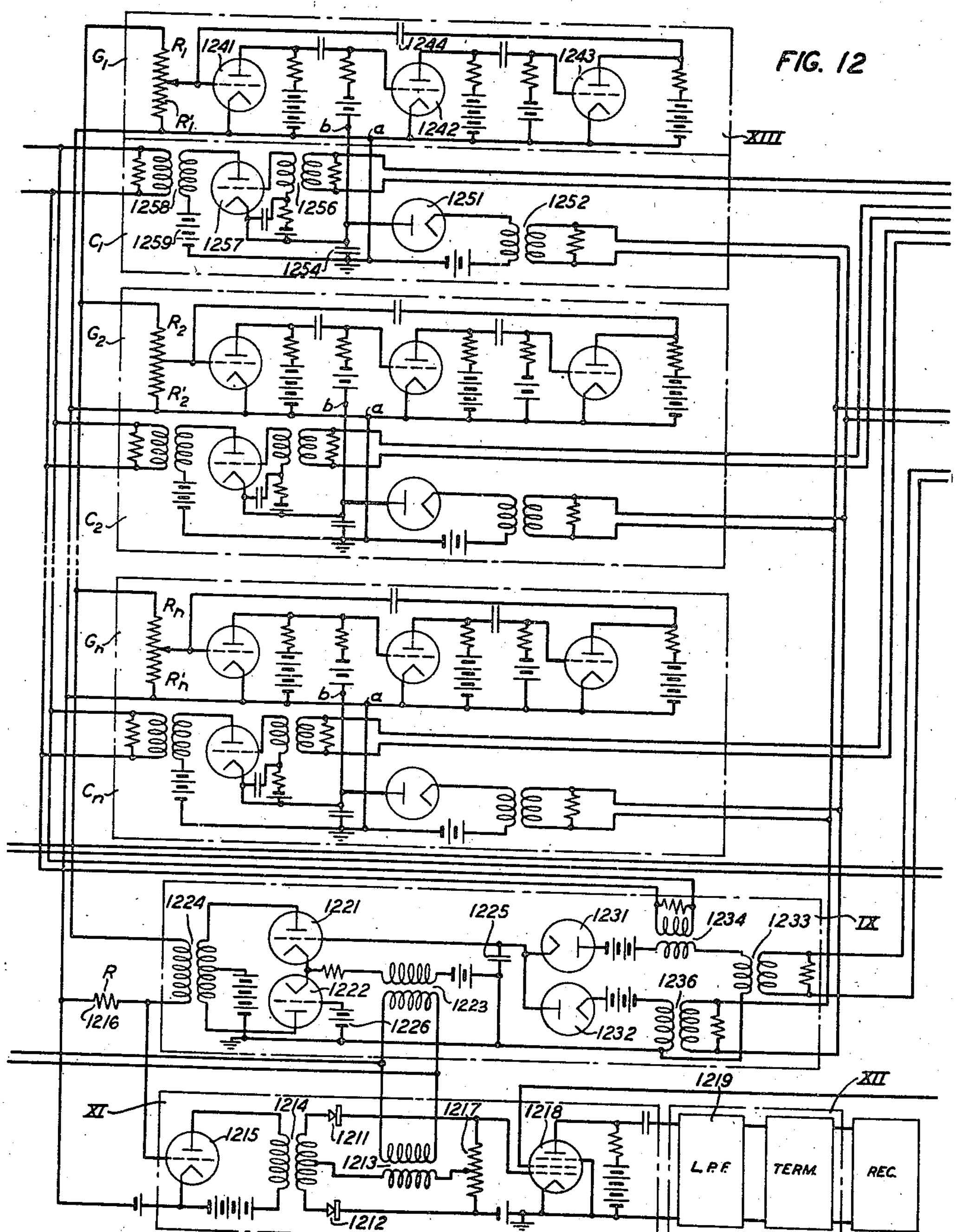
March 15, 1949. J. R. PIERCE 2,464,607

PULSE CODE MODULATION COMMUNICATION SYSTEM

Filed July 9, 1945

8 Sheets-Sheet 7

FIG. 12



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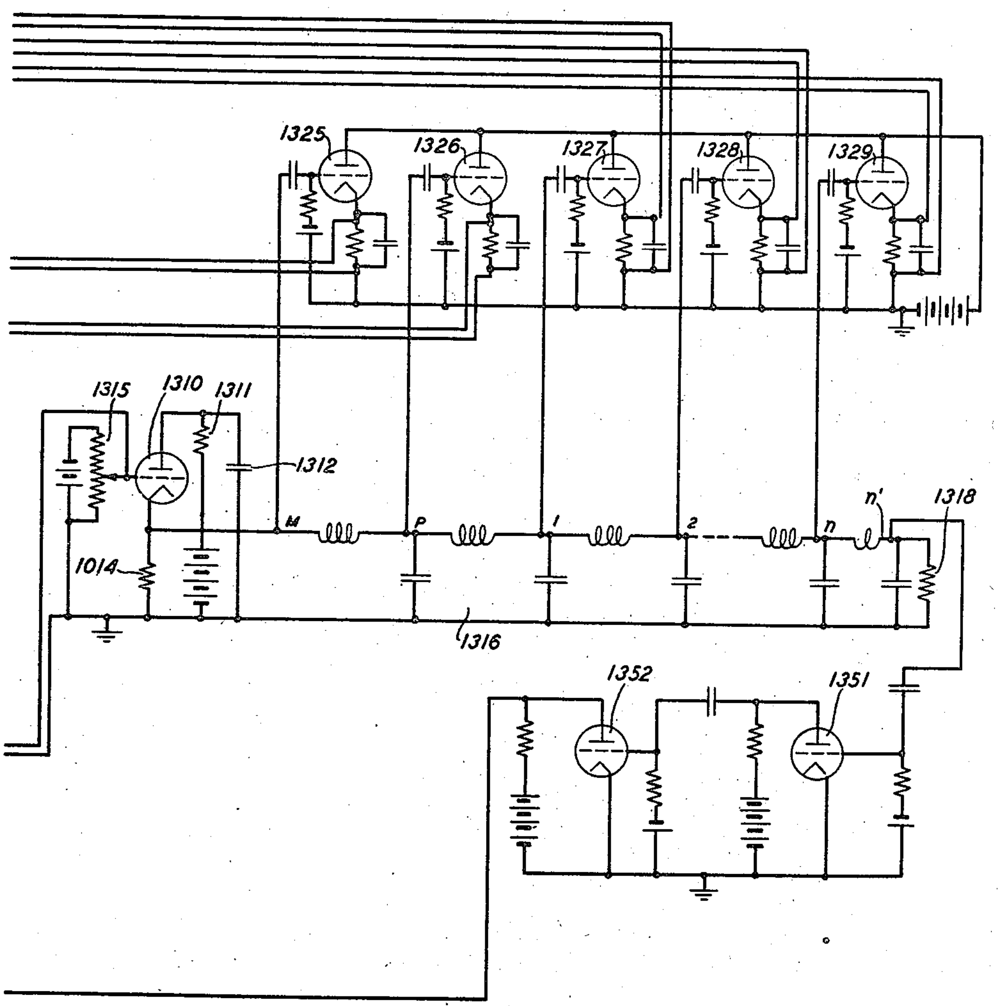
March 15, 1949. J. R. PIERCE 2,464,607

PULSE CODE MODULATION COMMUNICATION SYSTEM

Filed July 9, 1945 8 Sheets-Sheet 8

FIG. 13



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Patented Mar. 15, 1949 2,464,607

UNITED STATES PATENT OFFICE

2,464,607

PULSE CODE MODULATION COMMUNICATION SYSTEM

John R. Pierce, Millburn, N. J., assignor to Bell Telephone Laboratories, Incorporated, New York, N. Y., a corporation of New York

Application July 9, 1945, Serial No. 603,990

16 Claims. (Cl. 179—1.5)

1

This invention relates to communication systems for the transmission of complex wave forms of the type encountered in speech, music, sound, mechanical vibrations and picture transmission by means of code groups of a uniform number of impulses of a plurality of different types or signaling conditions transmitted at high speed.

An object of the present invention is to provide a communication system capable of transmitting and reproducing with high fidelity a complex wave form over an electrical transmission path in such a manner that the signal-to-noise ratio of the received signal is materially improved over the signal-to-noise ratio through the transmission path.

Another object of this invention is to provide improved and simplified methods and apparatus capable of transmitting and receiving signal impulses over a channel having a low signal-to-noise ratio and deriving therefrom signals having a high signal-to-noise ratio. In one sense this is obtained by using a wider band width, that is, trading band width for signal-to-noise ratio.

More specifically, it is an object of the present invention to provide methods of and circuits and apparatus for transmitting in succession a group of pulses in sequence over a given channel representative of the amplitude of a complex wave at successive instants of time. The pulses to be transmitted are, in general, of short duration so that the duty cycle of the various elements of the system is low, thus permitting large momentary power without overloading various elements, such large power tending to override such noise as may be inherently present, giving thereby a more favorable signal-to-noise ratio. Also by such low duty cycle combined with suitable "gating" arrangements at the receiving station the amount of noise picked up at the receiver may be correspondingly reduced.

It is a further object of the present invention to provide improved apparatus for determining the code to be transmitted to represent each of a large number of different amplitudes without the use of complicated counting circuits, arrangements and equipment.

A feature of the present invention relates to methods and apparatus for determining the magnitude of an electrical quantity and transmitting a series of pulses representative of said amplitude.

Another feature of the invention relates to methods and apparatus for building up an electrical quantity which is proportional to and a measure of the amplitude of a sample of a complex wave at a given instant. This quantity may take on the nature of a conductance or an admittance.

2

Still another feature of this invention relates to methods and means to perform building up of this electrical quantity step by step by an additive or a subtractive process to a total which is proportional to the amplitude of a sample of a complex wave.

Another feature of the invention relates to the use of conductances to be so built up by an additive or subtractive process to the total required.

Another feature relates to the transmission of information in the form of a code regarding each conductance added or subtracted.

This application is related to my copending application Serial No. 603,989 filed July 9, 1945, and its general objects and features are the same. It differs from the disclosure of that application in a novel method of introducing at the transmitter a group of conductances in parallel and deriving a voltage which is proportional to the introduced conductances and is compared with the sample voltage, being made equal to it within the degree of fidelity contemplated in the system.

Briefly, in accordance with the present invention, equipment is provided for generating a control pulse or a group of pulses of predetermined time relation one with another. These control pulses are employed to control a code element timing circuit, which circuit in turn generates a series of very short pulses some of which are positive and some negative and some a combination of the two.

Apparatus is also provided for sampling or deriving an electrical quantity which is a function of the amplitude of a complex wave to be transmitted, this sampling means being under control of the control pulse generator. For each of the control pulses the code element timing circuit generates a series of code element timing pulses and these in combination with the sampling means derive an electrical quantity having a magnitude related to the magnitude of the complex wave at the time of the control pulse.

This electrical quantity takes on the character of an admittance which may be varied step by step, cooperating with the complex wave sample to determine the next step of variation in the admittance. More specifically, the electrical quantity is in the nature of a conductance made up of a plurality of conductances of different magnitudes which may be added to each other or omitted in such combinations as to yield a conductance related to the magnitude of the complex wave at the time of the control pulse. The control devices for the conductances operate in coordination with the complex wave sample to build up a total conductance which is proportional to the amplitude of the sample. Still more specifically, the added conductance gives rise to a potential difference which is proportional to the amount of conductance which has been added and it is the purpose to so adjust the conductance that the potential difference developed is equal to the signal sample voltage. Accordingly, the potential difference is compared from instant to instant, as a smaller and smaller change is made in the conductance, to see whether the potential difference is in excess of or below that of the signal sample. If in excess of the signal potential difference, the last added conductance is removed; if below the signal potential difference the added conductance is left in.

In the specific illustration of my invention given herewith the plan is followed that if the magnitude of the conductance due to the last addition is in excess of that required, then it is removed and an "on" signal is transmitted. If the addition is below that required, then it remains in and information to this effect is passed to the remote point by the absence of the transmitted signal, the identification of the information being specified by the time at which the informational pulse is transmitted or not transmitted.

This form of comparing the sample with the potential difference set up by the conductance is then carried on step by step to as far a point as may be desired and in any case to an extent so that the granularity of the signal finally reproduced at a receiving point will be within the limits of fidelity contemplated for the system.

While thus setting up a code of pulses completely characterizing the amplitude of the complex wave sample, these pulses are transmitted. At the receiving station a control pulse generator, code element timing generator and a system of conductances to be introduced or not introduced, all analogous to those of the transmitting station are provided. In addition, decoding apparatus is provided in which the received pulses are employed to produce an electrical quantity having a magnitude similar to the magnitude of the complex wave sample of the transmission end of the system and thus the complex wave is reconstructed from a succession of such reproduced wave samples.

A feature of this system as a whole is that the measurement of the sample voltage is on a linear basis, i. e., the sum of the steps making up the electrical quantity is proportional to the sample voltage. In this respect the system is to be distinguished from one in which the measurement is on a decibel basis, as in my copending application, Serial No. 592,961 filed May 10, 1945.

The invention itself, both as to its organization and method of operation together with other objects and features thereof will be better understood from the following description taken with the accompanying drawings in which:

Figs. 1 and 2 show in functional block form the various elements and the manner in which they cooperate to form an exemplary communication system embodying the present invention;

Figs. 3 and 4 illustrate the timing and nature of the pulses and waves characteristic of my system;

Fig. 5 is explanatory of the method and apparatus used for measuring or determining the amplitude of a complex wave sample;

Figs. 8 to 13, when positioned as shown in Figs. 6 and 7, give in detail the various circuits, equipment and operation of an exemplary system embodying the present invention; and

Fig. 9A is explanatory of a portion of Fig. 9.

Fig. 14 is a circuit diagram of a control portion of a conductance.

Referring more specifically to Fig. 1, let M be a modulating function representative of any complex wave such as a speech wave, a small portion of which is indicated by curve 301 of Fig. 3. A modulator sends out a series of signals after times t_m, $t_{m+1}=t_m+T$, $t_{m+2}=t_m+2T$ and so forth. Each series consists of $1+n$ signals of the "on"-"off" variety. (The signals need not be on or off but each signal distinguishes between two positions called "on" and "off." These might be positions of time, frequency or amplitude. "On" might be transmitted as a current being "off" and "off" as that of current being "on.") The first signal of the series or group is used to tell the polarity of the function M at the time t_m. The next n signals of the group specify the magnitude of M at t_m with respect to some arbitrary unit of voltage or current. These n signals may be of such a character and so combined (advantageously on a binary system and so described in this specification for illustrative purposes) as to represent a large number of different amplitudes. Thus, for the case of 8 channels there may be sent, between t_m and t_{m+1}, the series of signals—on, on, on, off, on, off, on, off, or 00010101. The first zero carries the information that M is of negative polarity and the remaining signals that M is of amplitude 21 times the arbitrary unit value employed, this value being obtained by binary counting. A group of pulses of this type may be regarded as a permutated series of impulses in which the "on" conditions represent "marking" selections and the "off" conditions represent "spacing" selections or vice versa.

One specific means for obtaining such a series of signals is illustrated in the block diagram of Fig. 1. The over-all functioning will be described first and the possible nature of the block units will be described later.

While the functions described could be carried out without frequency conversion, grounding problems are simplified by first impressing the modulating function M on a balanced modulator I of Fig. 1, together with the output of a local oscillator II of frequency f_0, high compared with the frequencies occurring in M. At the time t_m shown on Fig. 3, a pulse which will be referred to as an M pulse, from a pulse generator VI is impressed on I. During the interval T between t_m and t_{m+1}, when another impulse is impressed on I, the modulator output current I_m has a frequency f_0 and an amplitude proportional to M at t_m, being plus when M is plus at t_m and minus when M is minus at t_m. At t_{m+1} another sample of the complex wave is taken and for the next interval T the modulator output has the same frequency f_0 and the new amplitude. This is indicated in Fig. 3 in which the graph 302 in the second line shows the potential across a condenser (later to be described) and the graph 303 in the third line shows the oscillations of frequency f_0 associated with the successive M pulses. It should be noted that if M is negative, as in the last group shown in line 1, this is recorded by a reversal of phase of the modulated current of frequency f_0.

I_m is fed to a balanced transformer III. This and the local oscillator II are very low impedance sources.

Two homodyne detectors are fed with signals in opposite phase from the balanced transformer. In series with these is the drop across a resistance R caused by current flowing from terminals *c*, *d* of the local oscillator II through conductances $G_1 \ldots G_n$. This drop will be proportional to $G_1 + \ldots G_n$. In series also is an output from terminals *d*, *e* of local oscillator II. This is adjusted to be equal and opposite to the drop across R caused by the current flowing through $G_1 \ldots G_n$ in their minimum conductance condition. Thus the voltage across *d*, *e* taken in series with the drop across R is proportional to the change in $G_1 + \ldots G_n$.

A polarity and amplitude detector is shown at V. The two inputs A and B from the homodyne detectors IVA and IVB are shunted with biased diodes so that the voltage across their outputs can never become negative or positive by more than a certain fixed amount regardless of the input to the homodyne detectors.

At the start of the cycle of operation associated with any one sample of the complex wave, all of the conductances are set in minimum condition. One of the homodynes will have positive output, the other negative. A pulse is then applied to polarity and amplitude detector V. If the polarity of M is negative, an impulse is sent to the transmitter VII and this, perhaps in conjunction with a pulse from VI, causes the transmitter to send an "on" signal. If the polarity of M at t_m is positive, V sends no pulse to VII and either VII emits no signal, meaning "off" or a pulse from VI causes VII to send an "off" signal.

The conductances, $G_1 \ldots G_n$, are electrically controlled. Control of these from "off" to "on" condition causes changes in conductance corresponding to the digits of a binary number of the type mentioned. Thus, for the case previously given of $1+n=8$, the total conductance is specified by 7 digits. Turning the various G's off and on in this case changes conductance by the amounts listed below:

Minimum conductance	$G_m < G_0$
Change caused by G_1	$64G_0$
Change caused by G_2	$32G_0$
Change caused by G_3	$16G_0$
Change caused by G_4	$8G_0$
Change caused by G_5	$4G_0$
Change caused by G_6	$2G_0$
Change caused by G_7	G_0

Thus the total conductance range is G_0 to $127G_0$ in steps of G_0. This makes possible a range of about 42 decibels with respect to the smallest step. The conductances $G_1 \ldots G_n$ are controlled electrically by (*a*) pulses from the pulse generator VI, and (*b*) the amplitude output of the polarity and amplitude detector V. The character and timing of these pulses are shown in Fig. 4 which is an expansion of the time interval between two sampling pulses or the time required for one cycle of operation. Here the second time interval T is shown expanded. The negative portion of the M pulse resets the modulator I and the positive portion immediately thereafter takes the sample of the complex wave. At the same time the initial negative pulse shown on lines 1 to *n* of Fig. 4 places all G's in the minimum conductance condition. In the meantime the sample of the complex wave causes operation of the homodyne detectors IVA and IVB. Then a polarity pulse at a time indicated by the P line of Fig. 4 is applied to V and information on the polarity of M is transmitted. Following this, a plus pulse is applied to G_1 at a time indicated by line 1 of Fig. 4. This puts in $64G_0$ of conductance. Immediately thereafter a negative pulse is applied to G_1. If the added drop across R due to the introduction of G_1 is less than signal voltage, then the condition of G_1 does not change and the conductance stays in. No impulse is sent to transmitter VII and either no signal is sent, indicating "off," or a definite "off" signal is sent by a pulse from VI. If, however, the added drop across R exceeds signal voltage, then G_1 is removed by the negative pulse and at the same time a pulse imparting that information is sent to the transmitter VII. This, perhaps in combination with a pulse from VI, causes VII to send an "on" signal.

Next, positive and negative pulses are applied in turn to $G_2 \ldots G_n$ at instants indicated by lines 2 to *n* of Fig. 4, resulting in insertion of conductance and transmission of "off" signals or in insertion and subsequent removal of conductance and transmission of the "on" signals.

After the $1+n$ signals specifying the polarity and the amplitude at t_m have been sent, VI sends a resetting pulse to the conductances. This puts all G's at minimum conductance condition. This pulse may also send a "marker" signal from the transmitter denoting the end of one interval or cycle of operation and the beginning of the next. This pulse may be simultaneous with the M pulse applied to I.

In a review of the operation of the system, reference may be made to Figs. 3 and 4, showing the character and time spacing of the pulses required from the pulse generator VI. At the top there is shown a series of pulses coming over the channel M to the modulator I and a sample of the complex signal wave at the instant of each modulator pulse is taken. Operating on an electrical element the sample causes the modulator to emit, until pulsed again, a current I_m of frequency f_0 and amplitude proportional to M at t_m. All this is indicated in the second and third lines of Fig. 3. A polarity pulse to the polarity and amplitude detector V arrives an interval later and this is succeeded by pulses over the channels 1, 2 . . . . *n* which operate on the conductances $G_1, G_2 \ldots G_n$. There is also a pulse channel T to the transmitter, necessary if the "off" signals are transmissions and not merely omissions. All this is shown in Fig. 4 which is an expansion on a time basis of one of the sampling periods of the system.

At the time of the M pulse, channels 1 and *n* are pulsed with strong negative pulses setting $G_1 \ldots G_n$ in the minimum conductance conditions. Next the polarity and amplitude detector V is pulsed. This results in a pulse to the transmitter VII if the polarity is negative and an "on" signal, or no pulse to VII if the polarity is positive and an "off" signal.

The *n* amplitude channels are pulses in sequence, first positively and then negatively. The positive pulse inserts conductance, the negative pulse removes conductance if it is too large and in doing so sends an "on" signal, otherwise the conductance stays in and there is an "off" signal. The channel T may apply pulses to the transmitter VII at all times whether an "on," an "off" or a "marker" signal is to be sent. These pulses will give an "off" signal from the transmitter but in combination with a pulse from G_1 . . . . G_n or V may give an "on" signal. Channel T may be omitted in which case "off" signals will be omissions.

While a number of different types of devices may be contrived to perform the functions of the representative blocks of Figs. 1 and 2, a better understanding of the invention will be obtained by specific illustrations of circuits to accomplish the desired ends. These will now be described but it is to be understood that they are illustrative only and that my invention is not limited to the specific circuit arrangement shown.

Transmitter

For a description of the transmitting end of my system, reference should be made to Figs. 8, 9 and 10 in which the various block components of Fig. 1 are represented by the same Roman numerals.

The complex wave transmitted is impressed on the balanced modulator system I, this complex wave having come from any suitable source such as a microphone 805 through appropriate terminal equipment 806. It is then sampled periodically and goes through the process to be described in further detail.

Pulse generator VI

It will be advantageous to now describe the pulse generating system VI, one form of which is shown in detail in Fig. 10. The first controlling element in this portion of the system is a relaxation oscillator comprising a gas tube 1010. This relaxation oscillator is of a form well known in the art and includes a resistance 1011 for charging a condenser 1012. Assuming that to start with the condenser 1012 is discharged then on closure of the circuit it is charged at a rate determined by the resistance 1011. When the potential of the condenser and consequently the plate of tube 1010 rises to a "firing" value, the condenser suddenly discharges through the tube and resistor 1014. The duration of the discharge is short and gives rise to a sharp positive pulse across the resistor 1014. The duration of this pulse and the rate at which it is followed by identical pulses, can be completely controlled by the parameters of the circuit; in particular, by the values of the elements 1011 to 1014 taken with the potential of the grid of tube 1010 as determined by the potentiometer 1015. While any of several forms of relaxation circuits may be used at this point the one shown is simple and satisfactory. Its operation is more fully described in many places, such as on page 184 of "Ultra-High Frequency Technique" by Brainerd et al., published by Van Nostrand Company, 1942.

The positive pulse from 1014 is now used to control the emission of pulses to various parts of the circuit. This is accomplished by connecting across the element 1014 a delay circuit 1016 made up of identical sections of inductance and capacitance connected seriatim. A positive pulse travels through this network, the time of arrival at each section being uniformly spaced and giving rise to corresponding positive pulses going out over channels 1, 2 . . . . n for purposes to be described. The delay network is terminated by a load 1040 of proper value to suppress any reflected wave.

The parameters of the relaxation oscillator may be adjusted so that pulses are derived across resistance 1014 at any frequency desired. For the purposes of my invention it is preferred to have a sampling frequency higher than that of the highest frequency component in the complex wave to be transmitted. If, for example, this wave is to be a speech wave and it is desired to transmit all components up to 4,000 cycles then there should be at least two samples per cycle of this highest frequency component. A suitable value, therefore, for the relaxation oscillator frequency would be 8,000 cycles although a higher value may be used, if desired.

By means of the delay circuit or "timestick" 1016, one has available at the ends of the respective sections, positive pulses similar to that initiated in 1014 and spaced in time, one after the other by an interval determined by the elements in a section of the timestick. At time t_m when the pulse is formed at 1014 (or point M) it is transferred immediately to tube 1020 and is then transferred to I as the M pulse of Fig. 3. The function of this pulse will be described hereinafter.

At one element of time later the positive pulse from 1014 will have reached the point P on the timestick and this will be identified as the P pulse. This P pulse operates on the grid of tube 1021 to give a positive pulse over the resistor 1022 which pulse is transmitted to the polarity and amplitude detector V, appearing there as a positive pulse of a form and at a time indicated by line P of Fig. 4.

At the end of succeeding elements of time the positive pulse from 1014 will arrive at points 1, 2 . . . n of the timestick and then be transferred respectively to the grids of tubes 1081, 1082, 1083, etc. Each of these pulses in its subsequent path is converted into a positive-negative pulse in a manner and for the purpose hereinafter described.

In addition to these pulses it is desired to send a group of corresponding pulses to the transmitter VII which pulses will be identified as T pulses and are indicated in the bottom line of Fig. 4. It will be noted that the first pulse in this cycle is longer than the subsequent pulses, this for reasons which will appear later. The first T pulse may, for instance, be approximately twice the length of the subsequent pulses. For the formation of the T pulses a chain of tubes 1024 to 1029 is provided. The grid of tube 1024 is operated on directly by the pulse from M. In the cathode circuit there is included the resistance 1031 paralleled by the condenser 1032. A positive pulse is generated across 1031 and the duration of this pulse would ordinarily be the same as the duration of the M pulse. However, the addition of a condenser 1032 will lengthen this pulse and the condenser is so chosen as to approximately double the duration. The positive pulse from 1031 is applied to the grid of 1025, the cathode circuit of which includes the resistor 1030. At the time of the M pulse on the timestick there is then transmitted over the T channel to the transmitter VII a positive pulse of approximately twice the duration of the M pulse. As the positive pulse over 1014 reaches successively the points P, 1, 2 . . . n the grids of the tubes 1026 to 1029 are operated upon and set up positive pulses across resistor 1030 which is a common cathode resistor for all the tubes 1025 to 1029. Consequently there is transmitted the desired series of positive pulses to the transmitter VII indicated in Figs. 4 and 8. For the purpose of synchronizing these pulses with the remainder of the equipment, delay circuits may be introduced wherever necessary. One such delay circuit is shown in the T channel at 1050.

Following the M pulse and the P pulse the number of sections in the timestick will usually be made equal to the number of digits required for setting up the amplitude code to be transmitted from VII. If there should be n of these then the number of possible codes by permutation of "on" and "off" signals would be 2^n. Thus, if number of digits in the code is seven this will make possible 128 combinations so that in the system it will be possible to discriminate between amplitudes of 128 different values.

Associated with conductor 1 from the timestick and tube 1081 is a circuit comprising tube 1061 and transformer 1071. The tube 1061 is shown as a double triode. The grid of the left-hand section of this tube receives a positive pulse at t_m which is then converted at the plate to a negative pulse. This negative pulse is transferred through transformer 1071 as a negative pulse to the control of the corresponding conductance device G_1 in Fig. 9 and serves as hereinafter described to set this conductance element to a minimum conductance. Shortly thereafter a positive pulse arriving over conductor 1 to tube 1081 is inverted and appears as a negative pulse on the grid of the right-hand section of tube 1061. However, the load circuit of tube 1081 includes the inductance 1091 which causes the negative pulse generated on the plate of 1081 to be immediately followed by a positive pulse so that the pulse arriving on the grid of the right-hand section of 1061 is a negative-positive pulse. This pulse in turn is inverted by the right-hand section of tube 1061 to a positive-negative pulse which is then transmitted through the transformer 1071 to the control circuit of conductance G_1. The character and timing of this positive-negative pulse is that indicated in line 1 of Fig. 4.

A similar circuit is associated with each of the conductors 2, 3 . . . n to give at the time of the M pulse a negative pulse to the corresponding conductance control devices setting each conductance to a minimum conductance and at a later time transmitting a positive-negative pulse to the control devices of the respective conductances in the same manner and at times indicated by lines 2, 3 . . . n of Fig. 4.

Various electrical elements appear in the circuit associated with each of the tubes thus far described. Thus across the primary of the transformers 1071, etc., there appears the resistors r_1, r_2, and r_3. These are present elsewhere also and they are for the purpose and of a value to sharpen the pulses which are transmitted by the corresponding transformers and to suppress their differentiating action, thus preventing the setting up of a reverse pulse. Other elements all serve purposes well known to those skilled in the art and need not be described further.

Modulator I

A description will now be given of the modulator circuit I as shown in Fig. 8. A complex wave made up of numerous frequency components, the highest one of interest being for the present taken as 4,000 cycles, arrives at the primary of transformer 810. At time t_m a positive pulse arriving on the grid of tube 1020 is converted by transformer 1019 and is impressed as a negative-positive pulse on the plate and cathode of diodes 811 and 812. The negative pulse causes current to flow through 812 and discharges condenser 814. When the positive pulse arrives immediately thereafter it causes current to flow through 811 charging the condenser 814 to a definite potential, this potential being equal to the positive pulse plus that of the amplitude M at t_m minus a constant bias potential determined by battery 816. The grid of triode 820 is held at this potential minus a bias potential due to 821 until another pulse is applied at t_{m+1}. The output of the amplifier tube 820 appears as a voltage across the resistance 825 and controls the operation of a conventional balanced modulator of any suitable form. As here shown it involves two varistors v_1 and v_2. Associated with this balanced modulator is also a source of local oscillations II of frequency f_0 large compared to the pulse frequencies present in the system. In a manner well understood in the art there will appear in the secondary of transformer 830 a wave of carrier frequency f_0, the amplitude of which will be proportional to the potential across resistor 825. The phase of the voltage in the secondary of 830 reverses as the voltage across 825 reverses. The output of the secondary of 830 is connected to the grid circuit of a pentode 835 which in turn yields an output current I_m which is almost independent of the load consisting of tuned circuit 837 and associated elements appearing hereinafter.

Local oscillator II

The local oscillator II may be of any one of the suitable forms well known in the art yielding a substantially sinusoidal output of reasonably constant frequency.

Homodyne detector IV

Associated with the output of the pentode 835 is the transformer 901 which connects to two homodyne detectors IVA and IVB in a manner now to be described. The primaries of two transformers 903 and 904 are connected in series and transfer the modulated carrier of frequency f_0 to the input of amplifying tubes 905 and 906, the amplitude of this carrier being determined by the amplitude of the signal sample. A bridge circuit from the mid-point of 901 to the common point of 903 and 904 includes certain elements described below. The output of tubes 905 and 906 through transformers 907 and 908 is supplied to the two similar balanced demodulators IVA and IVB. These demodulators may take on any of the well-known forms. Here they are shown as each including a pair of varistors and being supplied with a carrier of frequency f_0 from the local oscillator through transformer 909. As a result, there will appear across the output resistors 911 and 912 a potential difference of pulse frequency.

As an illustration of the operation of the system, let it be assumed that at a certain instant the current in the secondary of 901 is in the direction indicated by the arrow, giving rise to currents as indicated in primaries of transformers 903 and 904. It will be assumed also that the poling of the transformers from the local oscillator is such for positive sample amplitudes as to make the terminal k plus with respect to l and the terminal m minus with respect to l. The symmetry of the system is such that the potential differences across 911 and 912 will be equal so far as input from transformer 901 alone is concerned and, during any one sampling period, constant and proportional to the same amplitude.

It is the purpose in this circuit to obtain a measurement of this sample amplitude and to this end I make use of a variable conductance.

This conductance is made up of a plurality of conductances which may be introduced or not introduced in parallel in any desired combination. This variable conductance will be described in detail later but at this point is represented by dotted line resistor **916** and will be referred to as conductance G.

The operation of the circuit to accomplish this purpose comprises a circuit connected from the mid-point of the secondary of **901** to the common point of the primaries of transformers **903** and **904**. Included in this branch is the secondary of a transformer **917** supplied from the local oscillator. A portion of this secondary supplies current through the conductance G in series with a resistance R and there will appear across the resistance R a potential drop due to the local oscillator frequency current flowing therein. The one end of resistor R is connected to an intermediate point of the secondary **918**, this point being so selected that when the conductance G (**916**) is at its minimum value the drop over R will be equal and opposite to the electromotive force across the upper portion of **918**. Thus the potential difference between *f* and *g* is equal to zero when the conductance G is at minimum. As noted heretofore, the transformers **901** and **917** and associated tubes supplying them are designed to act as very low impedance sources. If, also, the resistance R is small compared with the reciprocal of G at any of its values, then it can be shown that the change in drop over R and therefore the potential difference between *f* and *g* will be substantially proportional to the conductance G. This potential difference and its direction is indicated at any one instant by *e* and by the downward pointing arrow.

When *e* is equal to zero, corresponding to minimum conductance, the potential differences between *k*, *l* and between *l*, *m* will be equal. If, however, the conductance is increased so that *e* takes on a definite value then, for the directions indicated, it will be apparent that the current flowing through the primary of **903** will be reduced and that through **904** will be increased. Accordingly, the potential at *k* will become less positive with respect to the point *l* and the potential at *m* will become more negative with respect to *l*. If the polarity of the signal sample should reverse then the polarities across **911** and **912** will also reverse and this reversal may be used to indicate the polarity of the signal sample in a manner hereinafter described. Furthermore, the change in potential of the points *k* and *m* may be used to determine the amplitude of the sample, this being accomplished by so adjusting the value of G that the potential difference *e* reduces the current through one of the resistors, say **911**, to zero.

Polarity and amplitude detector V

The circuit arrangement for determining the polarity and amplitude is shown at V. Connected across the terminals *k* and *m* is the resistance **931**, the mid-point *q* of which will take on a potential midway between the potentials of *k* and *m*. The two outputs of the homodyne detectors IVA and IVB are shunted with biased diodes **932** and **933** so that the voltage can never become negative or positive by more than a certain fixed amount regardless of the input to the homodyne detectors.

Connected across the output of one of the homodyne detectors, say IVB, is the input of triode **934**. Also in the input circuit of the triode is included the transformer **935** which receives a pulse from tube **1021** of Fig. 10. This transformer tends to put a positive pulse on the grid of triode **934** but because of the potential difference from *l* to *m* and additional bias this tube is cut off when the sample amplitude is positive and thus no pulse is transmitted through the output transformer **936**. If, however, the polarity of the sample amplitude reverses, so that the potential difference over *l*, *m* reverses, then the pulse in transformer **935** renders the triode **934** conducting and a pulse is transmitted over transformer **936** to the transmitter VII, giving the information of negative polarity. The operation of the amplitude measuring feature will be described below.

Conductance III

In Fig. 9 there are shown a plurality of conductance circuits, $G_1 \ldots G_n$, and conductance control circuits $C_1 \ldots C_n$, one for each digit in the amplitude code. These conductances taken in parallel, in whatever combination desired, constitute the conductance G symbolically represented at **916**. Three such units are shown but inasmuch as their action is identically the same except for timing and conductance value, it is necessary to describe only one of these identified by the block III which includes the first conductance G_1 of the series and its controlling unit C_1.

The conductance circuit is essentially a shunt feedback amplifier. It includes the resistances R_1 and R'_1 connected in series, the intermediate point being connected to the three-stage amplifier including the tubes **941**, **942**, **943** with resistance capacitance coupling, there being a feedback connection from the plate of the last tube **943** through condenser **944** to the grid of **941**. There is either zero or a very large gain around the loop depending on whether the control voltage applied to terminals *a* and *b* cuts off one or more tubes in the loop or allows them to operate. In this instance the loop is opened by a sufficiently high negative bias on the grid of tube **942**. Under these conditions the conductance G_1 is essentially

$$\frac{1}{R_1+R'_1}$$

If a positive potential of sufficient magnitude arrives at the point *b* then the loop is closed and if the gain through the tube is high R'_1 is virtually short-circuited and G_1 is essentially

$$\frac{1}{R_1}$$

almost independent of gain. Thus a high accuracy of control of G_1 can be attained independent of tube characteristics. Whereas for illustrative purposes the control has been shown on one tube only, it may be desirable to control the bias on several or all tubes in order to open the loop completely.

The control circuit C_1 comprises a plurality of diodes **951**, **952**, **953** and associated elements. When a positive pulse over channel *l*, arriving through tube **1081** of Fig. 10, is applied, the diode **951** conducts, charging the condenser **954**, applying a positive potential to *b* and closing the feedback loop thus increasing the conductance G_1. This will be referred to as introducing G_1. Immediately thereafter, a negative pulse is applied through transformer **955** to diode **952**. If this is the only pulse present on **952**, that is, if insufficient positive bias is present from the amplitude detector V, the negative pulse discharges condenser **954** and opens the feedback loop thus removing the conductance. At the same time current flows in resistance **958** through diode **953** sending a negative pulse to the transmitter, resulting in the transmission of an "on" signal. If there is a positive bias of sufficient magnitude from the amplitude detector through diode **937** to be described later, the negative pulse through transformer **955** is not sufficient to cause current to flow through diode **952**. Consequently, the conductance remains in and no pulse is sent to the transmitter.

With the arrival of the next pulse, corresponding to channel 2 of the timestick, the sample voltage in transformer **901** is again tested by the introduction of conductance G_2, and its removal if necessary. Similar action follows for each of the remaining conductances.

The operation of polarity and amplitude detector V for testing or measuring the amplitude will be better understood by reference to Fig. 9A. If the potential difference e is equal to zero, corresponding to G at minimum, the potential k would be positive with respect to l by say V'_1; m would be negative by the same amount V'_2 so that the point q on resistor **931** would be at the potential of l. However, the limiting diodes **932** and **933** will not allow the potential of m to fall lower than a designated value V_2, or the potential of k to rise above an equal value V_1 and the potential of q will still be the same as the potential of the point l, say V_0. When G_1 is introduced the potential V'_2 would tend to become lower but is still limited to V_2. The potential V_1 also tends to become lower and is still limited to V_1. If sufficient conductance has been added so that e is slightly larger than the voltage in the lower half of the secondary of **901**, when the polarity of **911** reverses and k becomes negative with respect to l, attaining a value as low as V_3 which is the same as the potential V_2 at m; in other words, both k and l take on the same negative value and V_q also falls to this value originating a negative pulse from q. Connected to the point q is a circuit comprising the diode **937** and battery **938** which normally is sending a current to each of the resistors **956**, **976**, etc., in the control circuits in such a direction as to make the upper ends of these resistors positive, thus giving a positive bias to the cathodes of **952**, etc. With this drop across **956**, the negative pulse alone over channel **1** is not able to make diode **952** conducting and therefore condenser **954** is not discharged and the conductance G_1 remains in. When the voltage e exceeds the signal voltage, the negative pulse at q renders diode **937** non-conducting which is equivalent to sending a negative pulse to resistance **956**. In that event diode **952** becomes conducting, condenser **954** is discharged and conductance G_1 is removed. Thus it is seen that if the conductance introduced does not give rise to a sufficiently large voltage e, the conductance remains in, but if the conductance introduced is such that e exceeds signal voltage, then the conductance is first introduced and is then removed by the negative pulse at q. It will be noted that if the polarity of the signal at **901** reverses then the polarity of k and m also reverse. In this case the voltage e will reduce the current in **904** instead of **903**, thus reducing the potential of m. The potential of k tends to become more negative but is limited. When the cross-over point is passed the potential of m goes negative and q drops to the same negative value as in the first instance. Thus, q goes negative for excess value of e for either polarity.

With each succeeding amplitude code pulse the successive conductances $G_2 \ldots G_n$ are introduced and are allowed to remain or are removed. At the end of the cycle, the total amount of conductance introduced is that which will yield a voltage e as nearly as possible equal to that of sample voltage in transformer **901**.

If a conductance is introduced and remains in then no signal, corresponding to an "off" signal, is sent. If it is removed by the discharge of condenser **954**, current flows through resistor **958** setting up a potential difference which renders diode **953** conducting thus sending an "on" pulse to transmitter VII.

During the setting up of the conductances, pulses modulated on a suitable carrier will have been transmitted from VII bearing the information to the remote station on what conductances are being introduced. The amplitude of each of the pulses so transmitted from VII will be the same and each element of the signal is purely an "off" and "on" matter. Since only integers are sent such a signal can be repeated indefinitely without adding distortion or noise to the recovered intelligence, even though distortion and noise below a certain threshold level may be present in the repeaters. Thus, even for very high quality transmission the requirements on the repeater units are low. This makes possible transmission over long paths with many repeaters. The presence or introduction of noise in the transmission path from VII to the remote receiving station will be of no influence so long as the noise thus introduced is relatively small compared to the amplitude of the signal being transmitted over the path. Such noise, therefore, would not appear in the signal later reproduced.

The value of the various conductances is more or less arbitrary but, in general, it would be expected that the first conductance G_1 would be the largest, the remaining ones decreasing sequentially. Thus G_1 may be of a value such that the voltage e takes on a value of 64 units of potential difference, G_2 of such a value as to introduce 32 units and so for the succeeding ones as indicated on column 5 of the specification. If two or more conductors are introduced the value of e will be equal to the sum of the effects of these conductances taken individually and thus the total value of e can be made equal to the sample voltage, within a limit represented by the change due to the smallest available conductance G_0.

The action is made more clear by reference to Fig. 5 in which, exclusive of the polarity pulse, a five-unit code is to be used on a binary system. If, for illustration, the sample amplitude is slightly over **22** units on the scale of **32**, as shown at the left of Fig. 5, then G_1 is such a conductance that its introduction by the pulse over channel **1** results in a change in voltage e of 16 units. This is less than the sample voltage and therefore G_1 remains in and an "off" pulse is transmitted to the distance station. The positive pulse over channel 2 now introduces G_2 which adds another eight units to the voltage e giving a total of twenty-four conductance units and a total of twenty-four voltage units. This, however, is in excess of the sample voltage and therefore G_2 is removed, as indicated on Fig. 5 and an "on" pulse transmitted to the distant station. The pulse over channel **3** then introduces G_3 giving e a value of twenty units and this being less than the sample voltage it remains in so the No. 3 pulse is an "off" pulse. The pulse over channel 4 now introduces G_4 building e up to twenty-two units. Finally, the pulse over channel 5 introduces G_5 building e to 23. This is in excess of the sample voltage and therefore G_3 is removed. Thus a voltage e has been built up which is as nearly equal to the sample voltage across one-half of the secondary of 901 as is contemplated in the system.

The marginal voltage between V_1 and V_2 of Fig. 9A can be adjusted to as small a value as desired, this being controlled mainly by the biasing batteries of the diode limiters 932 and 933. In general, it should be adjusted to be appreciably less than that corresponding to the voltage developed by the smallest change G_0 in conductance, as this voltage appears at 907 or 908 after amplifications.

Transmitter unit VII

During this procedure there has been arriving at transformer 850 a series of pulses over channel T, one for each pulse from the pulse generator, timed as indicated on the bottom line of Fig. 4. These pulses may be used to operate on a grid of the tube 855. In addition, there arrives at the transformer 852 certain pulses, one for each "on" pulse, relating to polarity or indicating that one of the conductances has been introduced and then removed. No pulse will come to the transformer 852 if a conductance has been introduced but not removed, this corresponding to an "off" signal. The secondary of the transformer 852 may operate on a second grid of tube 855 and this tube in turn controls the transmission or absence of transmission over a suitable medium to a remote station. In Fig. 8 it is shown as controlling a transmitting terminal unit 860 for a radio channel on a suitable carrier including carriers having wavelengths in the microwave region where the waves have quasioptical properties of propagation. Also it is to be understood that the pulses coming from the tube 855 may go directly to any suitable transmission path such as a pair of wires, a coaxial cable, wave guide, etc. In such cases it is not necessary and may not be desirable to use the pulses for modulating a carrier. The connection of the transformers 850 and 852 are such that a pulse arriving at 850 alone will not cause the transmission of a signal but the simultaneous presence of a pulse on 850 and on 852 would be effective in causing such transmission and would correspond to an "on" signal. The purpose of the pulses coming over the T channel is to assure proper timing coordination of the transmission of signal pulses. In some instances such added precaution will not be necessary in which case the T channel may be omitted, including the chain of tubes 1024 to 1029 of Fig. 10 and the transformer 850. In this case also the adjustment of the transformer 852 and tube 855 is such that a pulse on 852 will then be sufficient to cause transmission.

Receiver

The problem of recovering the modulation function at the receiver station is somewhat simpler and will be described by means of the block diagram of Fig. 2. For the example here described pulses forming the signal appear at A for all "on" signals. A pulse generator VIII is synchronized with the incoming pulses, perhaps by means of a marker pulse such as the M pulse from the transmitting station, so that its operations coordinate properly with the incoming signals. This generator sends out pulses to various devices which also receive the signal. These received signal pulses alone cause operation. A signal pulse in conjunction with a pulse from VIII will prevent a device from operating.

At the time when the signal corresponding to polarity appears the pulse generator applies a P pulse to a phase shifter IX. If there is an "off" signal or no signal pulse the phase shifter is set to shift phase 180 degrees; if an "on" signal the phase shifter is set to shift phase zero degrees. The phase shifter remains in this position until receiving another P pulse.

The next pulse of the pulse generator is sent to an electrically controlled conductance G_1 which controls a change of conductance proportional to that of G_1 of Fig. 1. The conductance is initially at a minimum. If the received signal is an "off" signal, conductance is switched in. If an "on" signal is received this prevents operation and G_1 is left at minimum conductance position. The next pulse from VIII goes to G_2 at the same time that the signal from G_2 of Fig. 1 arrives and so on through G_n. Thus, the total conductance is made proportional to that introduced in Fig. 1 which gave rise to the "on" and "off" signals. Then at a short time later, perhaps the next marker pulse corresponding to time t_{m+1} at the sender, a pulse from the pulse generator enables the local oscillator X. This acts as a constant voltage source of desired frequency sending current through $G_1 \ldots G_n$ and resistance R and to the homodyne detector XI. R is made small compared to $(G_1+G_2+\ldots G_n)^{-1}$. From the voltage drop across R there is produced an output pulse from the homodyne detector XI nearly proportional to the amplitude of M at t_m. A reset pulse may follow the pulse to oscillator X. This will reset $G_1 \ldots G_n$ and phase shifter IX to the initial position. The pulses from the detector XI are passed through a low-pass filter XII. If the highest frequency f_m in the complex wave is $f_m=\frac{1}{2}T$ and if the low-pass filter has a cut-off of f_m, a signal proportional to M, but delayed perhaps by T seconds, is recovered at the output of the low-pass filter. Here T is the length of a period between t_m and t_{m+1}.

With this brief description of the block diagram of Fig. 2 we may now proceed to a more detailed description of devices which will accomplish the steps set forth above. It will be apparent to those skilled in the art that there are numerous circuit arrangements for accomplishing this. Certain specific circuit arrangements are here shown in Figs. 11, 12 and 13 but these are illustrative for the sake of concreteness and it is to be understood that many variations may be made without departing from the spirit of my invention.

Referring more specifically to Fig. 11 there is shown a receiving unit 1106, here indicated as a radio receiver associated with a suitable receiving antenna 1105. This unit 1106 is an entirely conventional radio receiver of any suitable type including a detector the output of which yields the pulse signals as a reproduction of the pulses arriving at the transmitting unit VII of Fig. 8. This code pulse message is amplified to any necessary extent as illustrated by the tubes 1108 and 1109 and the output of 1109 is shown as going to a plurality of control devices $C_1 \ldots C_n$, one associated with each of a plurality of conductances $G_1 \ldots G_n$, in a manner hereinafter to be described.

Receiver pulse generator VIII

A derived path from the output of 1108 passes through suitable amplifiers as shown at 1112 and 1114 and an output pulse therefrom is used to control a relaxation oscillator shown in Fig. 13. This relaxation oscillator, centering about the gas tube 1310, may be simpliar in every respect to the relaxation oscillator at the transmitting station and shown in detail in Fig. 10. Corresponding to each of the units 1010 to 1015 in Fig. 10 there are the units 1310 to 1315 in Fig. 13. The adjustment of the parameters in the relaxation oscillator of Fig. 13, however, is such that the circuit does not normally oscillate but is triggered off by a pulse arriving from tube 1114. Furthermore, the parameters of this relaxation oscillator are so adjusted that the circuit will be triggered off by the first pulse in a group (corresponding to the M pulse at the transmitter) after which the oscillator cannot be triggered off until the arrival of the next M pulse.

This is accomplished by the use of the long initial T pulse of Fig. 4 to which reference has been made. It is to be borne in mind that all pulses transmitted by VII are of the same amplitude. However, since the tube 1112 is essentially a constant current device, the voltage built up in the tank circuit 1113 is proportional to the duration of the incoming pulse and thus the pulses arriving at 1310 corresponding to the M pulses will be of greater, perhaps double, amplitude and so be able to trigger the relaxation oscillator, whereas the other pulses in the cycle will not.

In a manner analogous to that of Fig. 10 there is associated with the relaxation oscillator a timestick 1316 from which a series of pulses may be derived with a time spacing as nearly identical as may be necessary to the time spacing of the pulses derived from the timestick at the transmitting station. This timestick has an additional section given rise to a pulse indicated by n' and delayed only slightly behind the previous pulse. The function of the pulse n' will be given hereinafter. The timestick is terminated with a suitable impedance 1318 to suppress reflection. Also there is a series of tubes 1325 to 1329 from which a series of positive pulses derived from cathode followers is initiated corresponding to the pulses from the timestick.

Receiver conductances XIII

The utilization of the various pulses to control the setting up of a series of conductances $G^1 \ldots G_n$ corresponding to those set up at the transmitting station will now be described. Fig. 12 shows a plurality of conductances $G_1 \ldots G_n$ which may be identical with those at the transmitting station or may be proportional to them. Here again three such circuits are shown but inasmuch as their action is identically the same expect for timing, it is necessary to describe only one of these identified by the block XIII including the first conductance G_1 of the series and its controlling circuit.

The conductance circuit is again essentially a shunt feedback amplifier. It includes the resistances R_1 and R'_1 connected in series, the intermediate point being connected to the three-stage amplifier including the tubes 1241, 1242, 1243 with resistance capacitance coupling, there being a feedback connection from the plate of the last tube 1243 through condenser 1244 to the grid of 1241. There is either zero or a large gain around the loop depending on whether the

control voltage applied to terminals a and b cuts off one or more tubes in the loop or allows them to operate. In this instance, as in Fig. 9, the loop is held open by a sufficiently high negative bias on the grid of tube 1242. Under these conditions the conductance G_1 is essentially

$$\frac{1}{R_1+R'_1}$$

If a positive pulse of sufficient magnitude arrives at b then the loop is closed and if the gain through the circuit is high, G_1 is essentially

$$\frac{1}{R_1}$$

almost independent of gain. Again, whereas for illustrative purposes, the control has been shown on one tube only, it may be desirable to control the bias on several or all tubes in order to open the loop completely.

The control portion C_1 of the conductance may take on a large variety of circuit forms so long as it performs the desired function in response to the pulses reaching it and may comprise one or more diodes or combination of diodes and triodes or multigrid tubes in a variety of ways as will be clear to those skilled in the art. Specifically, in Fig. 12 it is shown as a combination of a diode with a triode. A positive pulse corresponding to the M pulse from the timestick operates through the transformer 1252 so poled as to make the cathode of 1251 negative whereupon any positive charge on the condenser 1254 is discharged and negative bias on the tube 1242 opens the conductance loop. This occurs simultaneously on all of the conductance units at the beginning of a cycle and sets all the conductances at minimum conductance.

In due course a pulse from circuit 1 of the timestick and tube 1327 arrives at transformer 1256 being so poled as to make the grid of triode 1257 positive, whereupon current flows through the plate circuit to give a positive charge to the upper plate of condenser 1254 thus closing the conductance loop. This is on the assumption that the only pulse acting on the tube 1257 is that coming from the transformer 1256 and this would be the condition for an "off" signal arriving at the receiver. If, however, there has arrived an "on" signal at the same instant then that signal operates through transformer 1258 in the plate circuit of 1257, and when properly poled will balance the effect of the positive pulse on the grid and no plate current will flow. Consequently, condenser 1254 will receive no charge and the conductance loop will remain open. Thus it is seen that conductance G_1 will be introduced if the corresponding conductance G_1 has been introduced at the transmitting station and if it has not been introduced at the transmitting station it will not be introduced at the receiving end.

The same operation will take place for each of the conductances $G_2 \ldots G_n$, after which the combination of conductances connected in circuit will be the same as that at the transmitting end.

Local oscillator X

The receiving station is provided with a local oscillator X shown in Fig. 11 as 1120. This may, but need not, be of the same frequency as the local oscillator II at the transmitting station. In other words, no synchronism between the two oscillators is required.

Phase shifter IX

Phase shifter IX is shown as comprising two triodes 1221 and 1222 the grid circuits of which are supplied in parallel from the local oscillator 1120 through the transformer 1223. The output circuit comprises transformer 1224, the midpoint of the primary of which is connected to the positive terminal of the plate battery. The grid circuit of tube 1221 contains the condenser 1225 and the grid circuit of tube 1222 includes the battery 1226 which tends to give a positive bias to the grid. Normally, therefore, the transconductance of tube 1222 will be higher than that of 1221 and there will be an alternating current of local oscillator frequency in the secondary of 1224. The phase of the current in the secondary current may, however, be reversed by means of the phase shifter. For this purpose there is included two diodes 1231 and 1232 biased so that normally they are non-conducting. When a pulse from the tube 1326 corresponding to P pulse arrives at transformer 1232 it is so poled as to render diode 1231 conducting, giving a positive charge to condenser 1225 of such magnitude as to give tube 1221 a higher transconductance than 1222, whereupon the current in the secondary of 1224 is reversed in phase. This reversal occurs if the pulse code at the transmitter was an "off" signal, meaning an absence of a received pulse. The condenser 1225 is so connected as to retain its charge for the duration of one complete cycle.

If, however, the polarity of the sample of the complex wave at the transmitter had been negative, then an "on" P pulse will have been transmitted and, in turn, received at the receiving station. A corresponding pulse, therefore, arrives at the transformer 1234 in parallel with the transformers 1258, etc., at each of the conductance control circuits. The transformer 1234 is so poled that its pulse opposes that of the pulse coming on transformer 1232 and consequently diode 1231 does not conduct, the condenser 1225 does not become charged and the phase of the oscillations in secondary of 1224 is not reversed. At the end of the cycle or the beginning of the next cycle the M pulse from tube 1325 operates through transformer 1236 to make diode 1232 conducting, whereupon the condenser 1225 is discharged or "reset" to normal condition. Through the means thus described it is seen that it is possible to change the phase of the local oscillator current in transformer 1224 by 180 degrees.

The secondary of transformer 1224 is connected in series with a resistance 1216 corresponding to R of Fig. 2. In series with this also is the combination of conductances $G_1 \ldots G_n$. Resistance 1216 is small compared to the resistance of the conductances taken in parallel. Also the tubes 1221 and 1222 should appear as a low impedance source by any suitable means, such as using tubes of low impedance, or by use of a cathode follower circuit or by a step-down transformer. In this case the current in and the voltage across 1216 will be proportional to the conductances which have been introduced and, therefore, proportional to the sample current or voltage at the transmitter.

Homodyne detector

The homodyne detector XI comprises a balanced demodulator including varistors 1211 and 1212 connected in a standard bridge circuit. The demodulator is supplied directly with local oscillator frequency through transformer 1213 and also with the same frequency through transformer 1214. The primary of transformer 1214 is included in the plate circuit of triode 1215, the grid circuit of which includes the resistance 1216. Thus the detected current of pulse frequency appearing across resistance 1217 will be proportional to the current in 1214 and therefore proportional to the amplitude of the complex wave sample. Furthermore, its polarity will be determined through the phase shifter IX to correspond with the polarity of the complex wave sample at the transmitter.

The last step of interpretation comes through the multi-grid tube 1218. This tube is normally biased to cut off. However, through the additional section of the timestick leading to the pulse n' previously referred to, a positive pulse is impressed on the triodes 1351 and 1352 connected in tandem to give requisite amplification without change of polarity of the pulse. Very shortly after the termination of the amplitude code there arrives then on one grid of tube 1218 a positive pulse of sufficient value to enable the tube 1218 for the duration of the pulse n'. During this interval then there appears in the output circuit of 1218 a pulse determined by the magnitude and polarity of the voltage over 1217, which latter is proportional to the amplitude and polarity of the complex wave sample.

These pulses will arrive in succession, one for each sample of the complex wave. By means of the low-pass filter 1219 the undesired high frequency components may be removed and the resulting wave passing to terminal equipment and receiver will be a reproduction of high fidelity of the original complex wave at the transmitting station.

In this specification my invention has been described in terms of very specific apparatus. This has been for the purpose of clarity but it will be apparent to those skilled in the art that many substantial variations may be made in the system without departing from the spirit of the invention. For example, Fig. 12 shows a specific arrangement for control of the conductances, which control comprises the diode 1251 and the triode 1257. A modification of this control circuit is shown in Fig. 14 in which the triode is replaced by a second diode 1253. The resetting pulse coming in over the transformer 1252 will discharge the condenser 1254 as before. A pulse from the pulse generator coming over transformer 1256 is so poled as to render diode 1253 conducting if that is the only pulse arriving. This permits the condenser 1254 to be charged and the introduction of conductance, this corresponding to an "off" signal. If an "on" signal arrives it is transferred through transformer 1258 to the diode 1253 but the transformer is so poled that its pulse will oppose the simultaneously arriving pulse over transformer 1256. Consequently, diode 1253 will not be rendered conducting, the condenser 1254 will not receive a charge and the corresponding conductance will not be introduced. Many other variations should also be borne in mind, for example, the T channel of pulses may be omitted with corresponding simplifications, although with some loss of control. Also the local oscillator at the receiving station may be on all the time instead of being triggered on occasionally, for even if left on it is ineffective at the terminal apparatus unless and until the tube 1218 has been enabled by the pulse coming from n'. Still further it will be evident that the modulation and demodulation features of the transmitter station may be omitted, the sample signals out of tube 820 going directly to the input of tube 835 and directly from tube 901 to the resistor 907, or its equivalent, without the intermediation of the demodulator in the homodyne unit IV. This would mean also the omission of the oscillator II. Corresponding alterations could be made at the receiving station in connection with its local oscillator. In general, however, such omissions or simplifications would lead to sacrifice in operation or quality and it would be a matter of engineering judgment as to how far one may carry out such simplifications.

This invention is related to my inventions described and claimed in my copending applications Ser. No. 592,961, filed May 10, 1945, and Ser. No. 603,989, filed July 9, 1945. It is the more closely related to the latter application and differs from it in that whereas in the system of that application conductances are added in parallel across the load circuit of pentode 835 until the residual voltage available across the conductances in parallel becomes less than a certain small reference level, in this application the introduction of conductances in parallel builds up a voltage e which is compared with and made equal to the signal voltage. Also in that system, the sum of the conductances $G_1 \ldots G_n$ in the low conductance position or state should be small compared with the smallest conductance step. In the present disclosure this restriction is not necessary because in that state the voltage e across R is balanced by the voltage in the upper portion of 918 and I find that certain advantages accrue thereby.

What is claimed is:

1. In a communication system in which the instantaneous amplitude of a complex wave is sampled at frequently recurrent intervals and then represented by a series of pulses of two different signaling conditions, apparatus for obtaining samples of the instantaneous amplitude of the complex wave, means for measuring each of said samples which comprises means for synthesizing a reference voltage by successively smaller and smaller steps, apparatus for comparing the synthesized voltage and the sample, and means for controlling the signaling condition of each of said pulses by said comparing means.

2. In a system for transmitting information on the shape of a signal from a transmitting to a receiving station, a transmitting station comprising means for sampling a signal wave periodically and storing on a condenser a potential proportional to the sample amplitude, an amplifier tube the input of which is connected across the storage condenser, a network in the load circuit of said tube including two similar detectors connected to receive the tube output in series, and means for increasing the current in one detector and decreasing the current in the other in proportion to the sample amplitude.

3. In a system for transmitting information on the shape of the signal from a transmitting to a receiving station, a transmitting station comprising means for sampling a signal wave periodically and storing on a condenser a potential proportional to the sample amplitude, means for impressing a voltage proportional to the condenser potential on a network comprising a pair of balanced impedances, and a circuit associated with the network and connected to a local source of current and adapted to unbalance the impedances, the voltage in said associated circuit being made proportional to the sample amplitude and serving to reduce the current in one impedance to zero.

4. In a system for transmitting information on the shape of the signal, a transmitting station comprising means for intermittently sampling a signal wave periodically and developing a potential difference proportional to each sample amplitude, a source of local oscillations, a modulator controlled by the local oscillator and the sample voltage to yield a modulated wave of local oscillator frequency, a network comprising a pair of balanced detectors and connected to receive the modulated wave, and a circuit associated with the network and connected to the source of local oscillations and adapted to unbalance the detectors, the voltage in said associated circuit being made proportional to the sample amplitude and serving to reduce the current in one detector to zero.

5. The combination of claim 1 characterized by means for equalizing the sample voltage with the voltage due to said synthesized voltage.

6. The combination of claim 1 characterized by the fact that the means for the step-by-step adjustment comprises a plurality of conductances connected in parallel and each normally possessing a minimum conductance but adapted to be brought to a larger preassigned conductance, and means for compensating the initial minimum conductance whereby the added conductance is proportional to the sample.

7. The combination of claim 4 characterized by the fact that the effective voltage in the associated circuit is made equal to the sample amplitude voltage by means of a plurality of conductances to be introduced or not introduced step by step in the branch circuit, and that there is present a pulse generator and means controlled to build up the conductances step by step by the coordination of the signal amplitude with pulses from the pulse generator until the output from one of the detectors is substantially zero.

8. The combination of claim 4 characterized by the fact that the effective voltage in the associated circuit is made equal to the sample amplitude voltage by means of a plurality of conductances to be introduced or not introduced step by step in the branch circuit, and that there is present a pulse generator and means controlled to build up the conductances step by step by the coordination of the signal amplitude with pulses from the pulse generator until the output from one of the detectors is substantially zero, the successive steps of conductance to be introduced or not introduced being in a decreasing order of magnitude the steps being multiples of the smallest and final step to be taken.

9. A system for transmitting information on the shape of a signal wave comprising a transmitting station and a receiving station the transmitting station comprising a circuit for periodically sampling the amplitude of the wave and for deriving a carrier frequency wave proportional to the said sample amplitude, a pulse generator giving rise to a plurality of cycles of pulses, one cycle for each sample, one pulse in the cycle detecting the polarity of the sample, a controllable conductance to be introduced in series with a source of voltage and a resistor, the current through the resistor being substantially proportional to the conductance, a plurality of the pulses in the cycle operating in coordination with the sample amplitude to introduce conductances

step by step from larger to smaller steps on an additive basis until the voltage drop across the resistor is equal to the sample amplitude.

10. A system for transmitting information on the shape of the signal wave from a transmitter to a receiver station the transmitter station comprising a circuit for periodically sampling the amplitude of the wave, a current source adapted to deliver a current proportional to the sample amplitude and constant for the duration of the sampling interval, a circuit for transferring the said current to a polarity and amplitude detecting circuit, a plurality of n conductances adapted to be connected in parallel with each other and in series with a resistor and a current source, a control circuit for each conductance, and a pulse generator to generate cycles of pulses, one pulse in the cycle serving as a marker pulse and as timing the sampling of the signal wave, another serving as a polarity pulse to cooperate in testing the polarity of the sample amplitude, the remaining pulses operating successively through the control circuits of the conductances in cooperation with the voltage drop over the resistor to introduce one or more conductance steps until the resistor drop is equal to the sample amplitude within an arbitrary small value.

11. A combination of claim 10 characterized by means to compensate for the resistor drop due to the conductances when in their minimum conductance state.

12. The combination of claim 10 characterized by a circuit associated with each control circuit to transmit one condition of signal if its conductance is left in and a different condition of signal if it is removed, the n conductances being graded in size from the smallest of value G_0, the largest being first tested for introduction, the system being so operated that the sum of the conductances introduced and left in at the end of the cycle is proportional to the sample amplitude.

13. The combination of claim 10 characterized by a circuit associated with each control circuit to transmit an "off" signal if its conductance is left in and an "on" signal if it is removed, the n conductances being graded in size from the smallest of value G_0, the largest being first tested for introduction, the system being so operated that the sum of the conductances introduced and left in at the end of the cycle is proportional to the sample amplitude, and further characterized by the fact that the wave sample is first modulated against a carrier frequency whereby the constant current referred to is of carrier frequency and the current source for the resistor and conductances is of the same frequency.

14. In a circuit for measurement of the polarity and the magnitude of an unknown alternating current voltage, a network including a pair of balanced detectors in series with the voltage source, a branch circuit supplied with current from an independent source of the same frequency as said unknown alternating current voltage, the voltage due thereto in an impedance tending to unbalance the detectors in a direction depending on the polarity of the source to be measured, means for adjusting the current through said impedance until the voltage across it is equal to the unknown voltage, indicated by the reduction of the current in one detector to zero.

15. The combination of claim 14 characterized by the fact that the means for adjusting the current comprises a plurality of conductances adapted to be connected in parallel in such amount as to be itself proportional to the unknown voltage.

16. In a circuit for the measurement of the polarity and the magnitude of an unknown voltage from an alternating current source, a pair of balanced homodyne detectors in series with the voltage source, a branch circuit supplied with current from a source of the same frequency as said unknown voltage and of constant voltage, the voltage due to said current in a resistor tending to unbalance the detectors in a direction depending on the polarity of the source to be measured and to yield rectified voltage of unequal value in the homodyne detectors; means for adjusting the current through said resistor until the voltage across it is equal to the unknown voltage, indicated by the reduction of the output of one homodyne detector to zero.

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