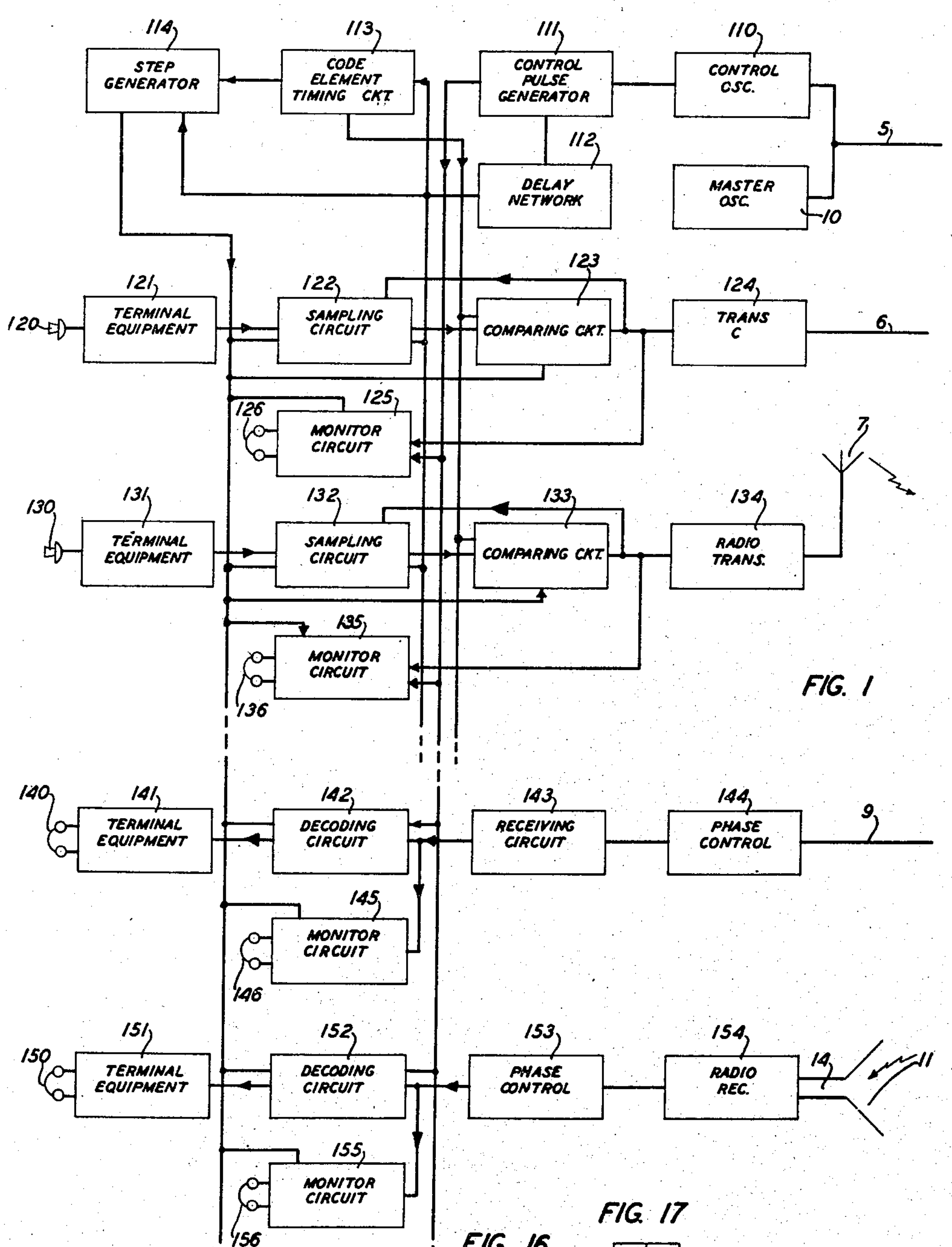

FIG. 1

FIG. 15

FIG. 1	FIG. 2

FIG. 16

	FIG. 5	FIG. 8
FIG. 3	FIG. 6	FIG. 9
FIG. 4	FIG. 7	FIG. 10

FIG. 17

FIG. 11	FIG. 13
FIG. 12	FIG. 14

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Sept. 14, 1948. W. M. GOODALL 2,449,467

COMMUNICATION SYSTEM EMPLOYING PULSE CODE MODULATION

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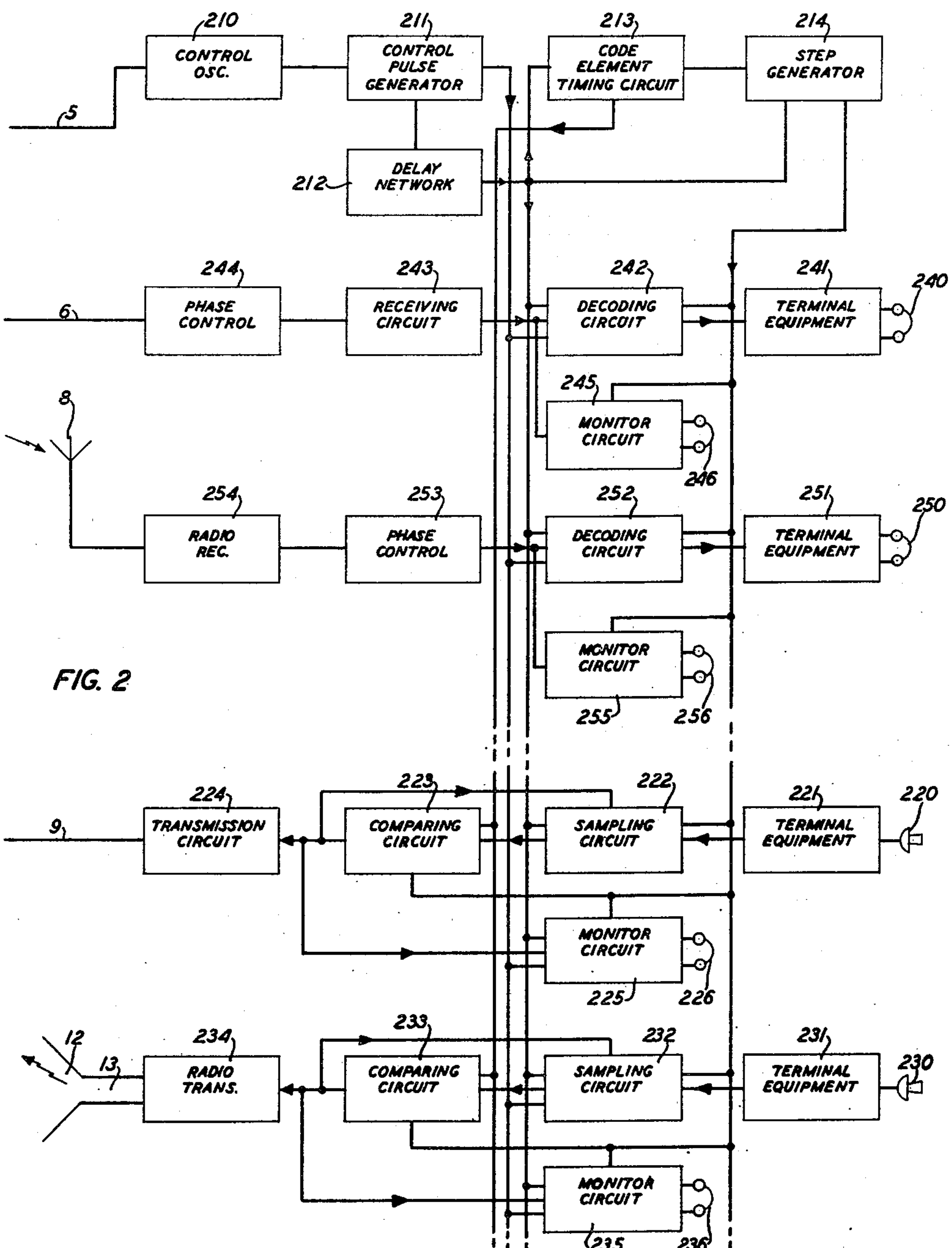

FIG. 2

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COMMUNICATION SYSTEM EMPLOYING
PULSE CODE MODULATION

Filed Sept. 16, 1944 12 Sheets-Sheet 3

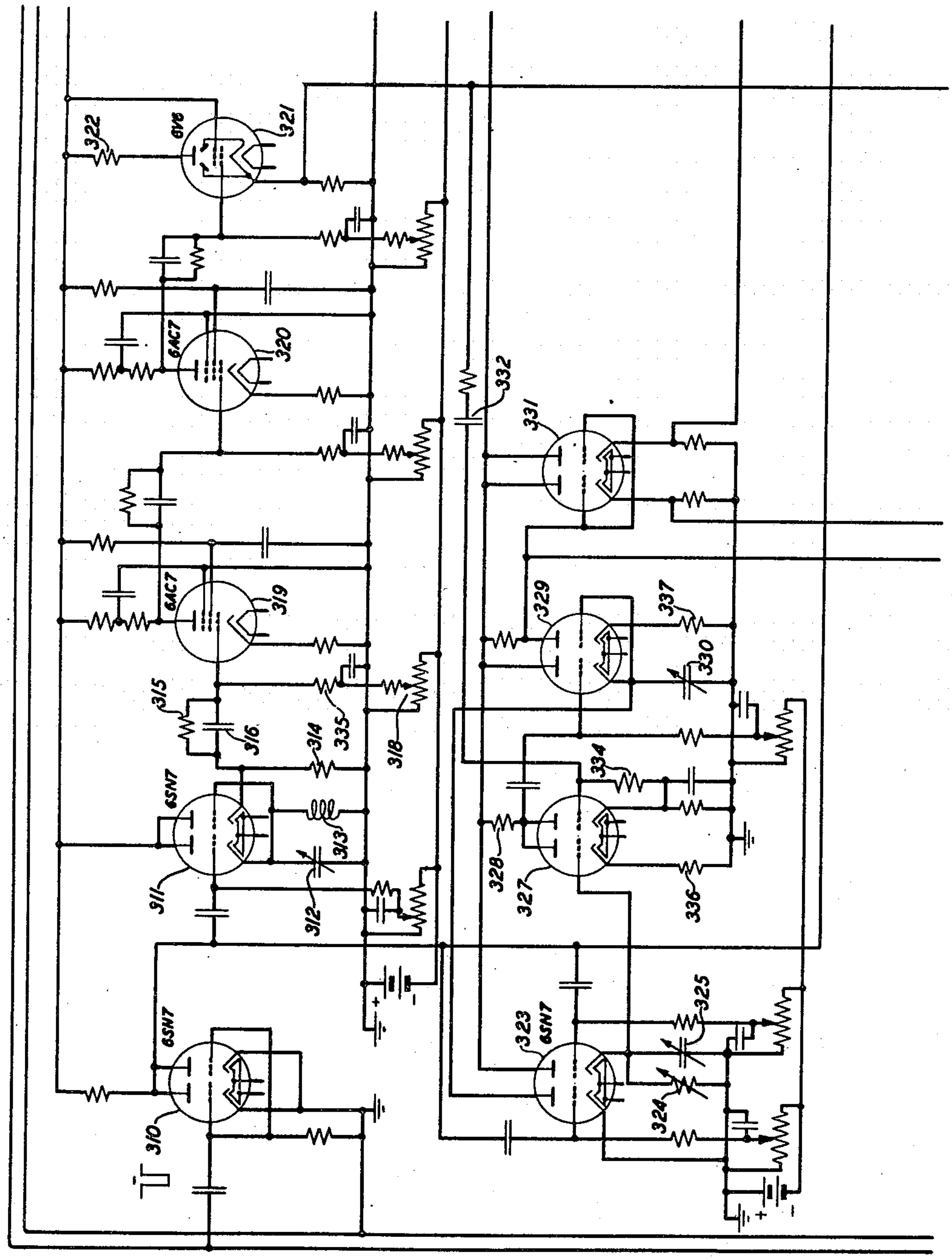

FIG. 3

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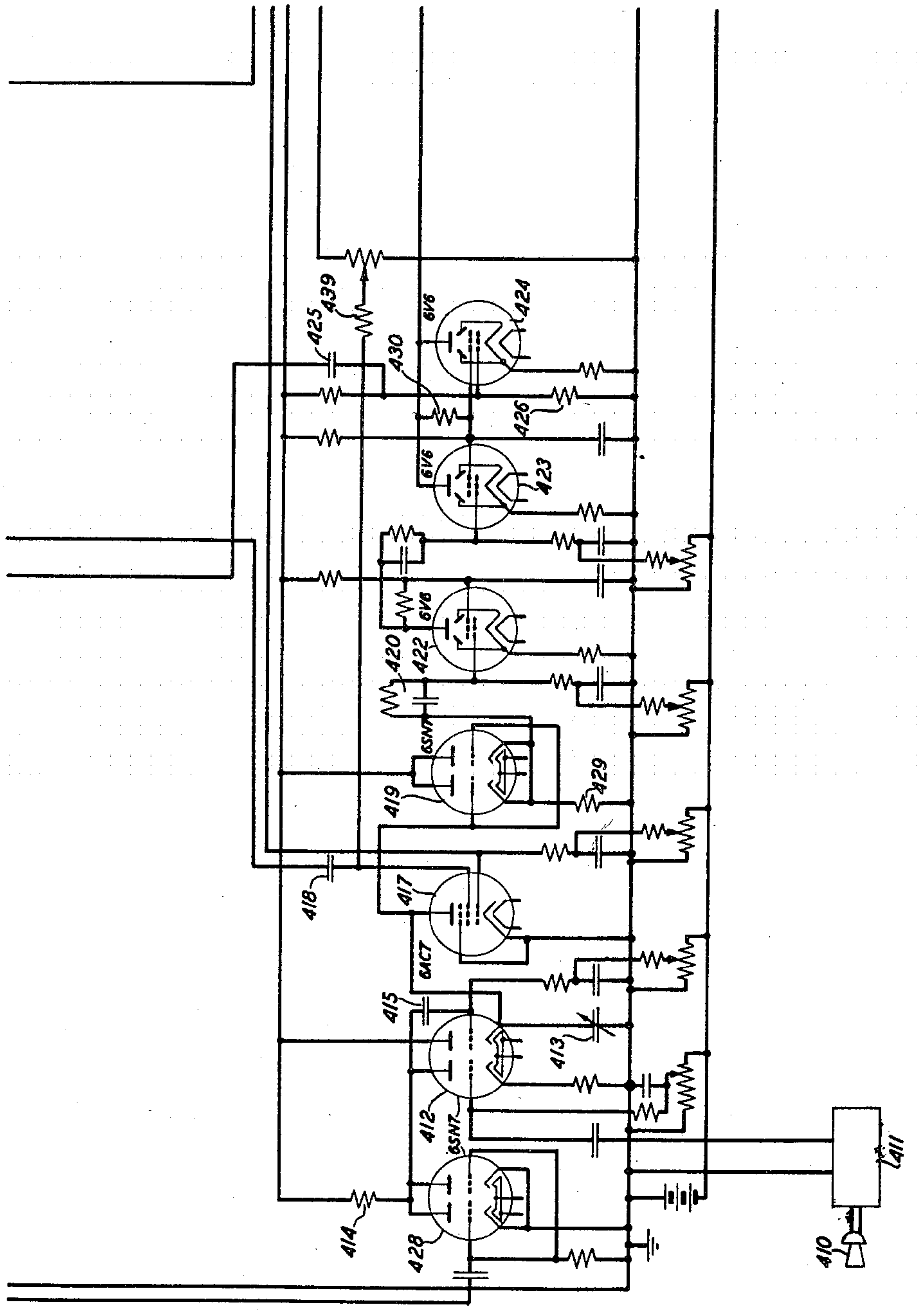

FIG. 4

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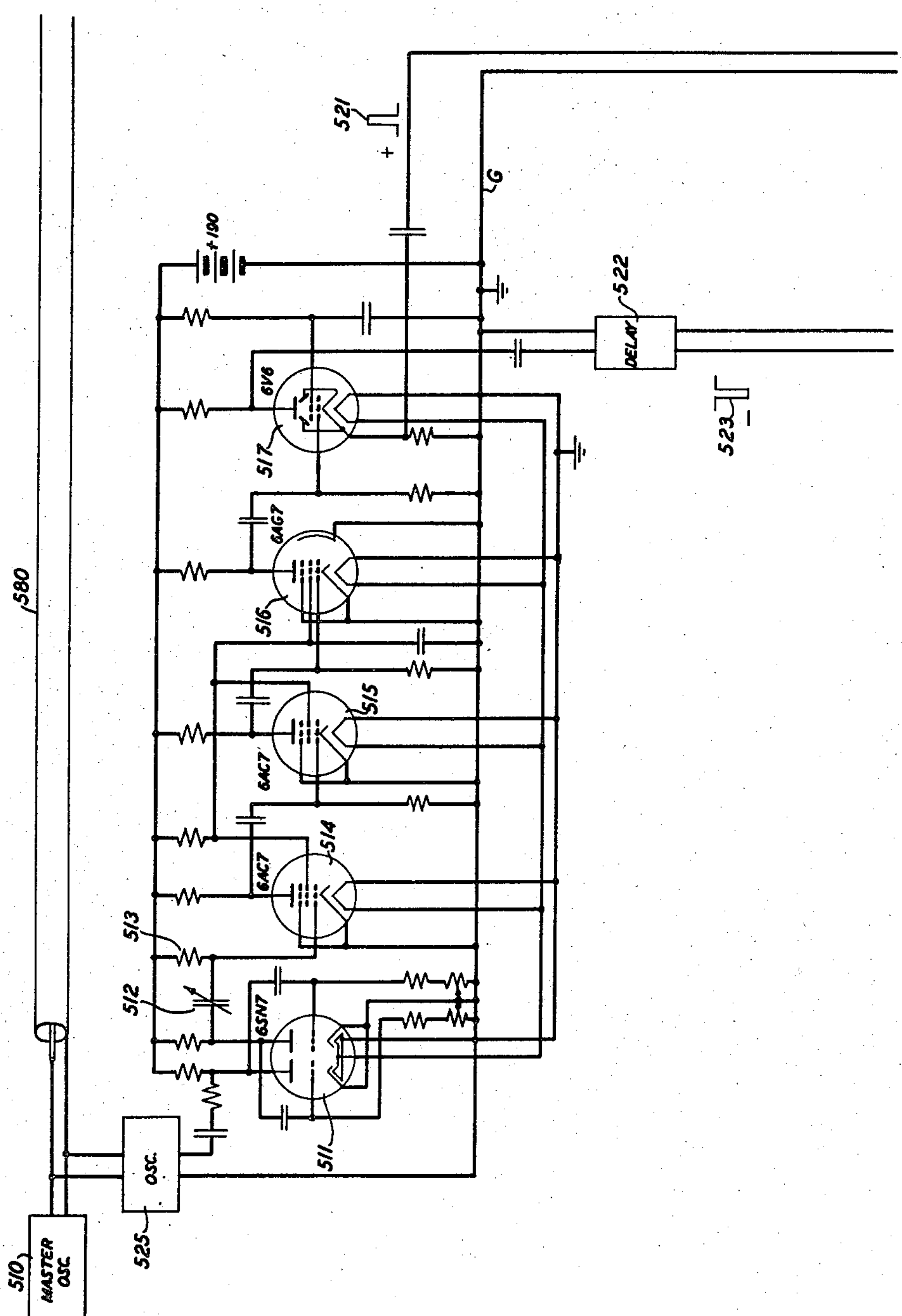
FIG. 5



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COMMUNICATION SYSTEM EMPLOYING PULSE CODE MODULATION

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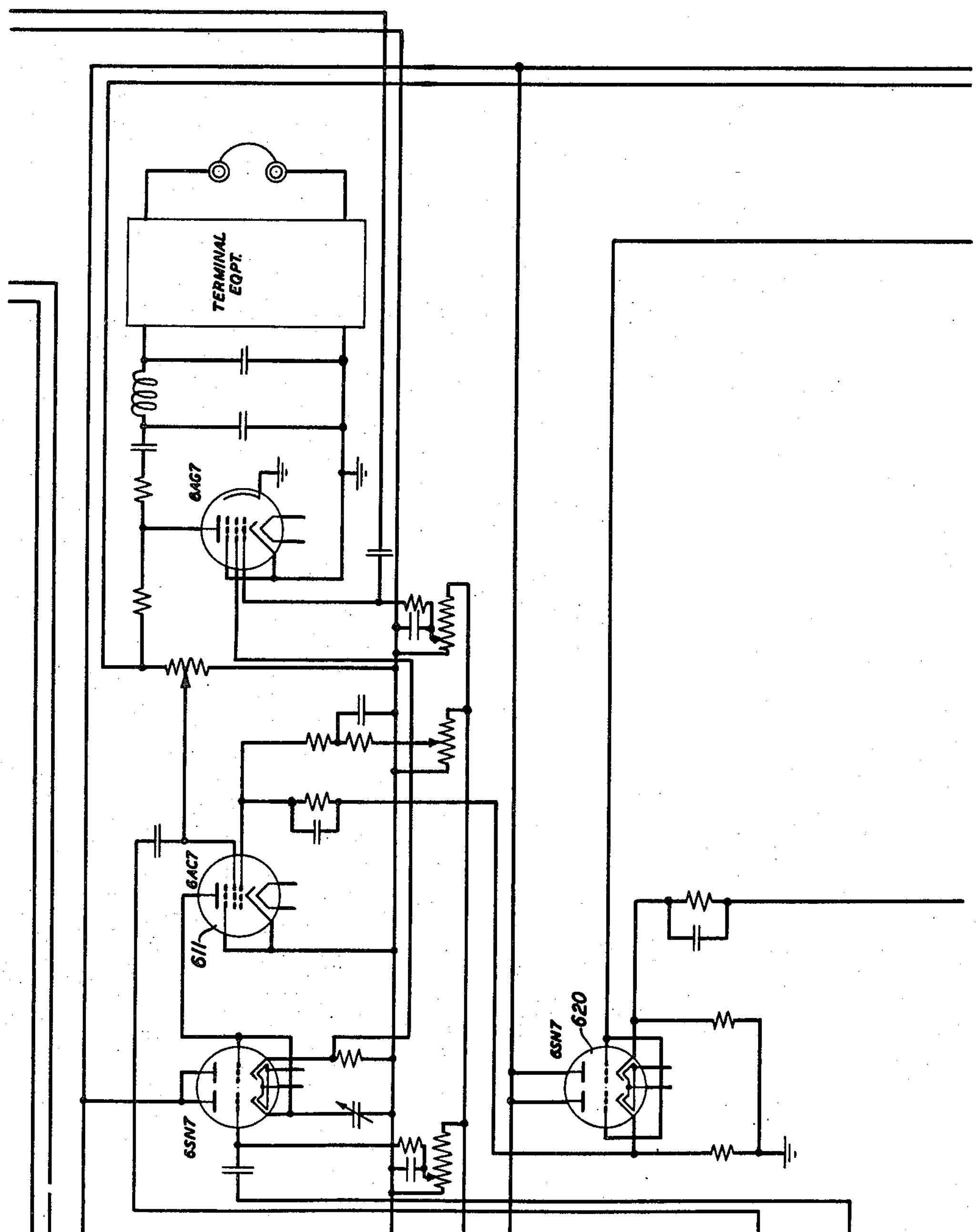

FIG. 6

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COMMUNICATION SYSTEM EMPLOYING PULSE CODE MODULATION

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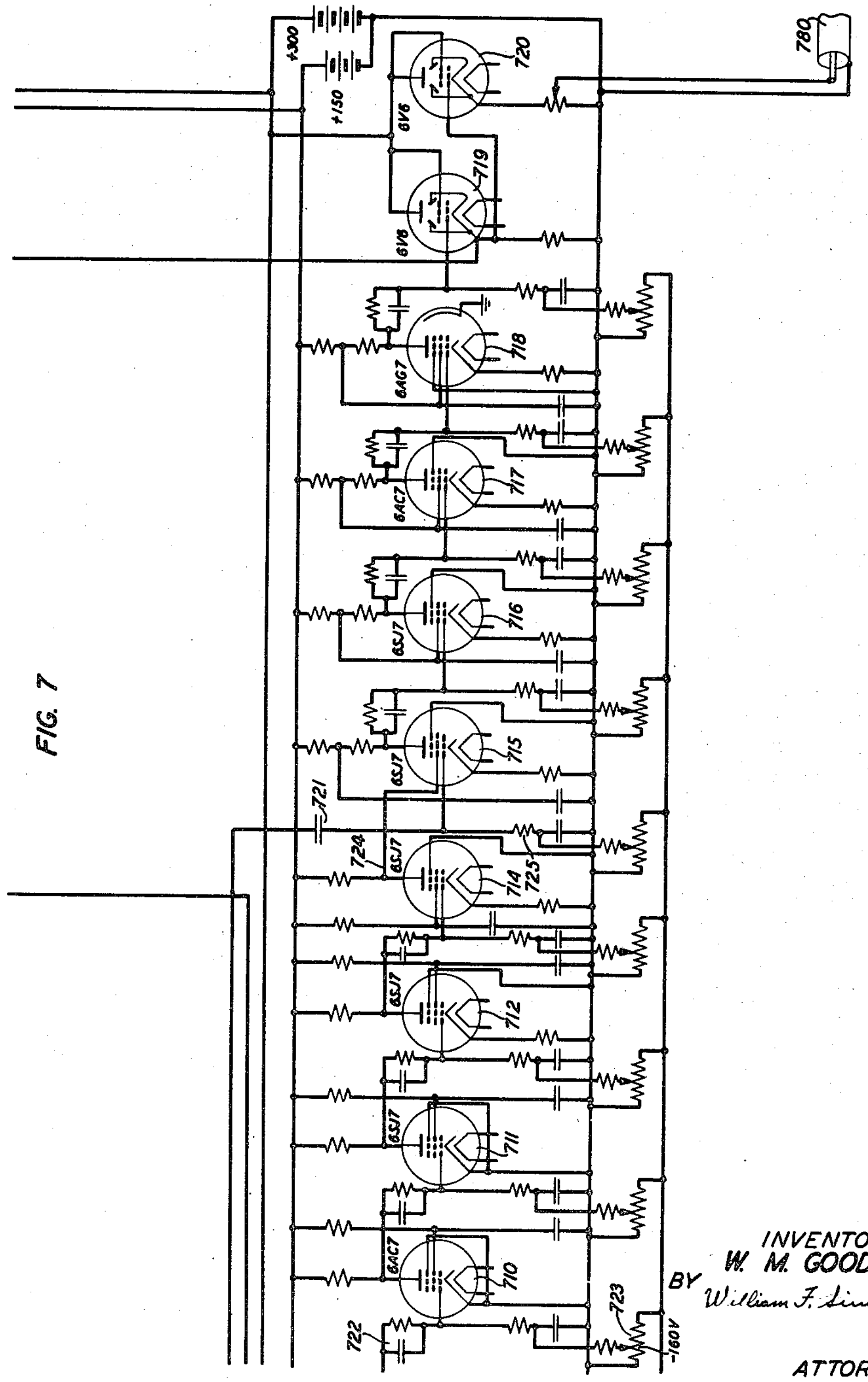
Filed Sept. 16, 1944

12 Sheets-Sheet 7



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COMMUNICATION SYSTEM EMPLOYING PULSE CODE MODULATION

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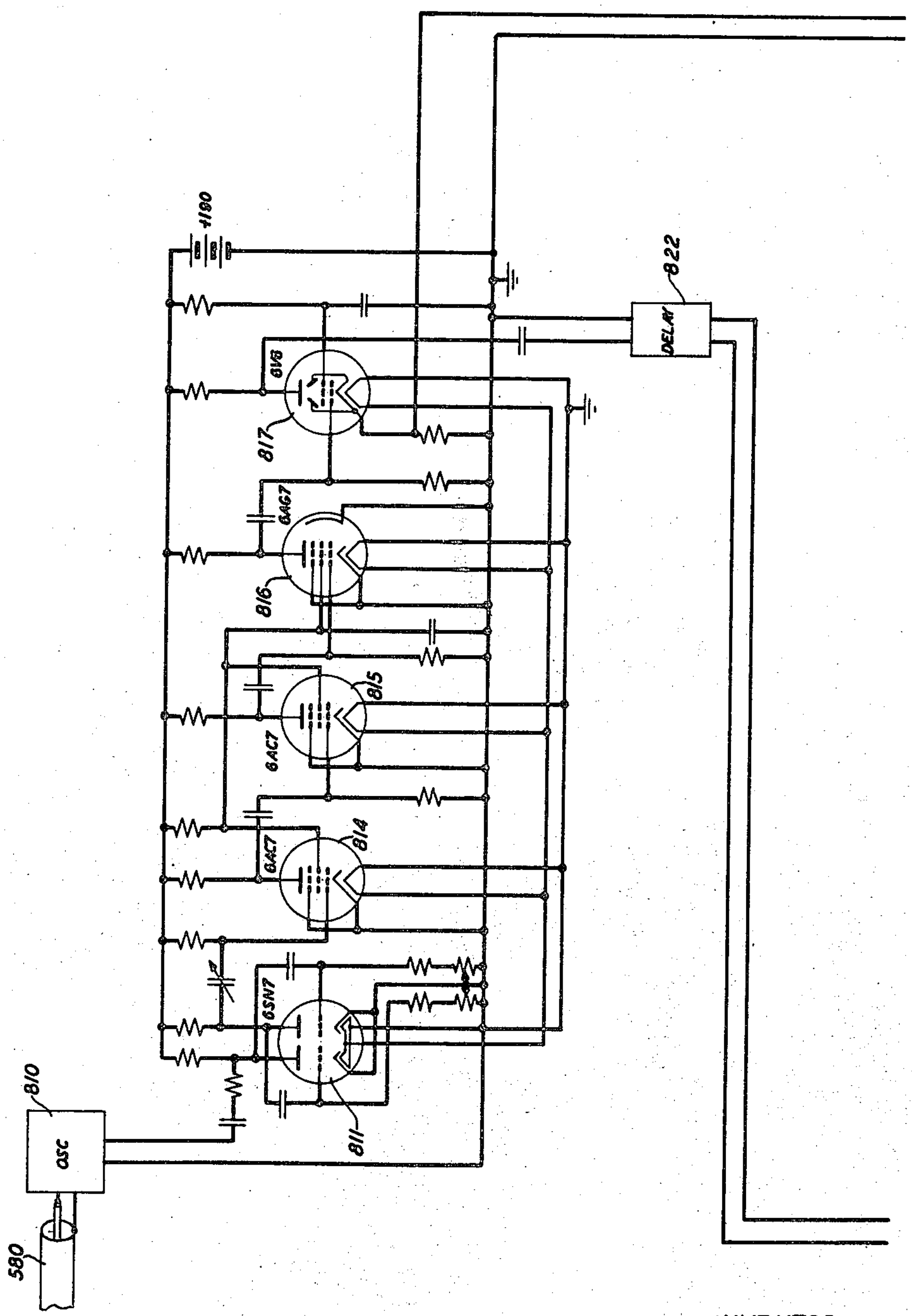
FIG. 8



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COMMUNICATION SYSTEM EMPLOYING PULSE CODE MODULATION

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12 Sheets-Sheet 9

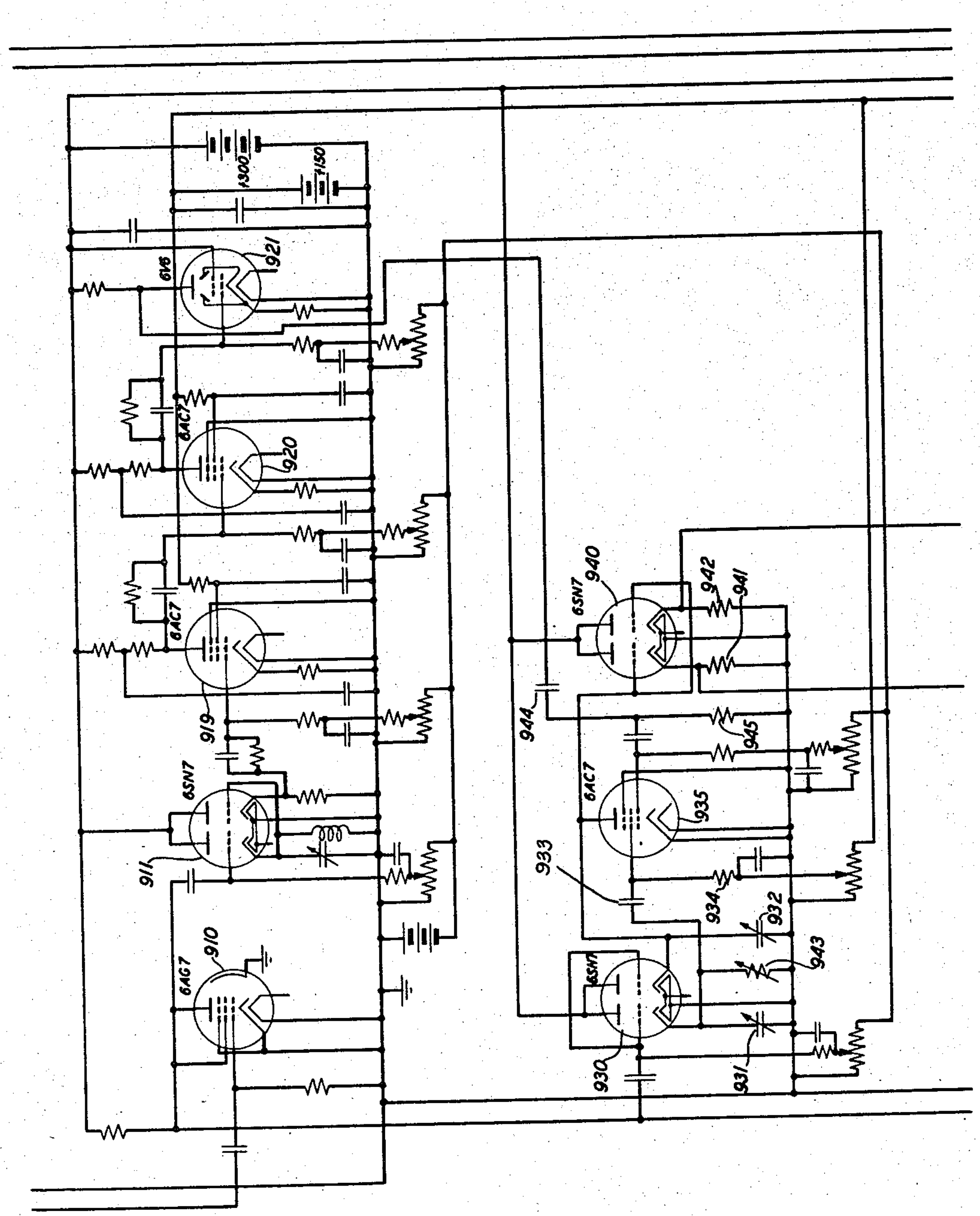

FIG. 9

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COMMUNICATION SYSTEM EMPLOYING PULSE CODE MODULATION

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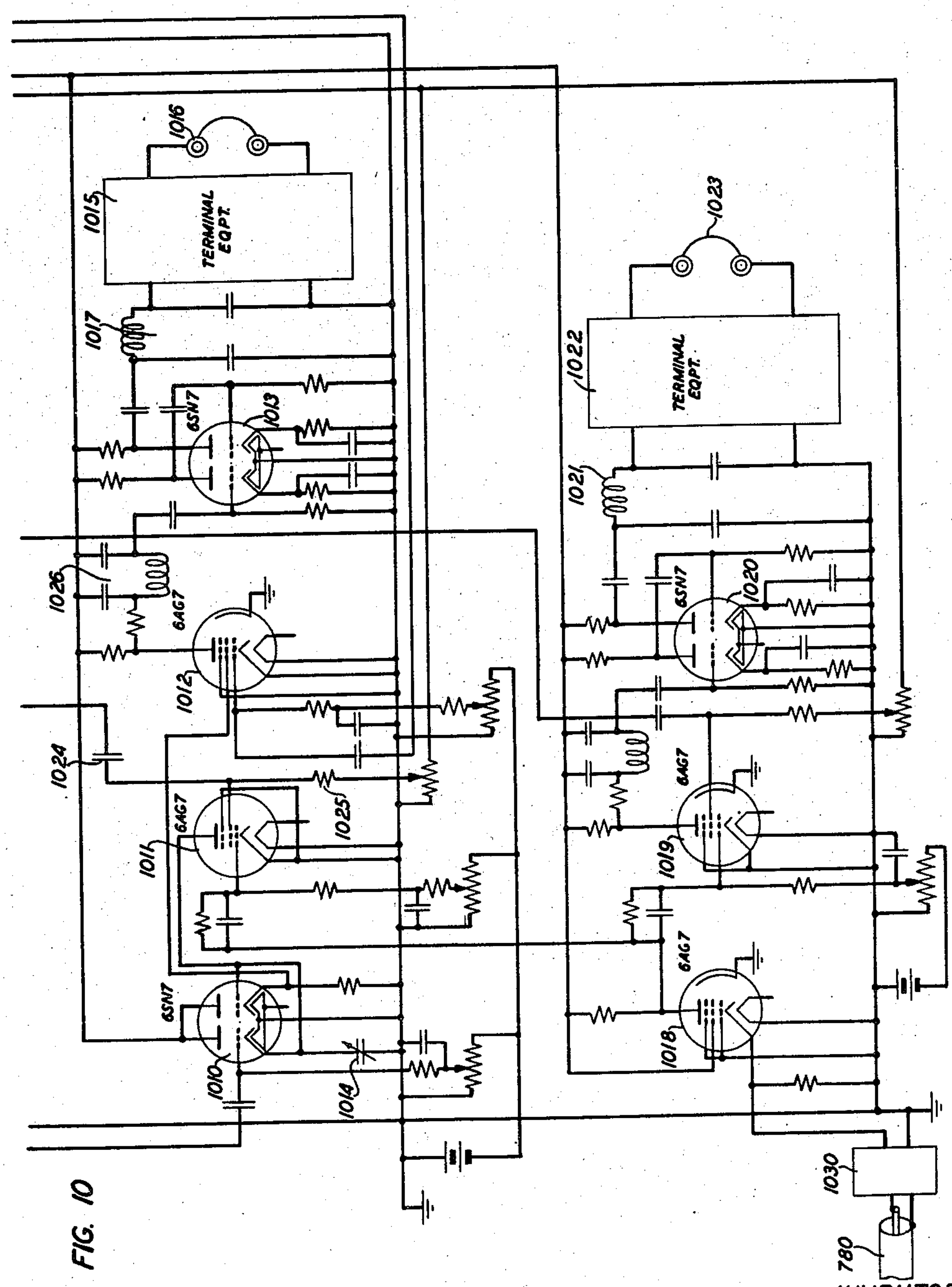

FIG. 10

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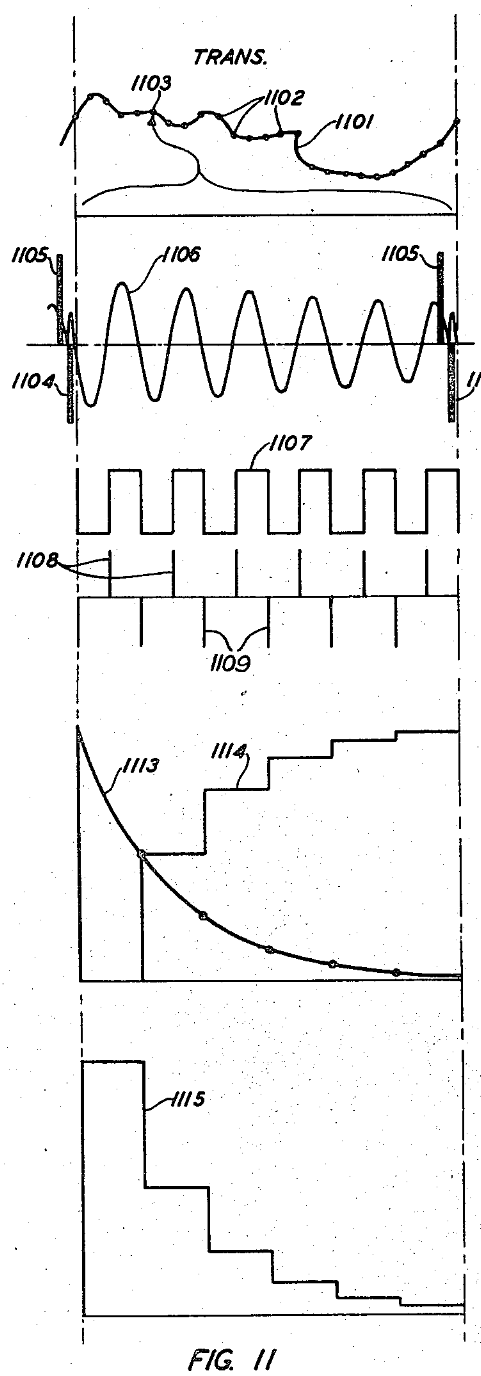

FIG. 11

FIG. 13

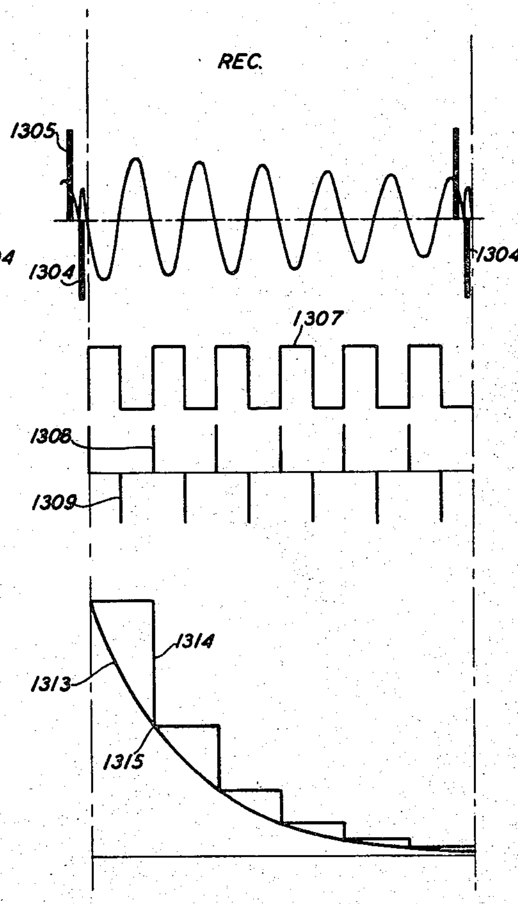

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FIG. 12

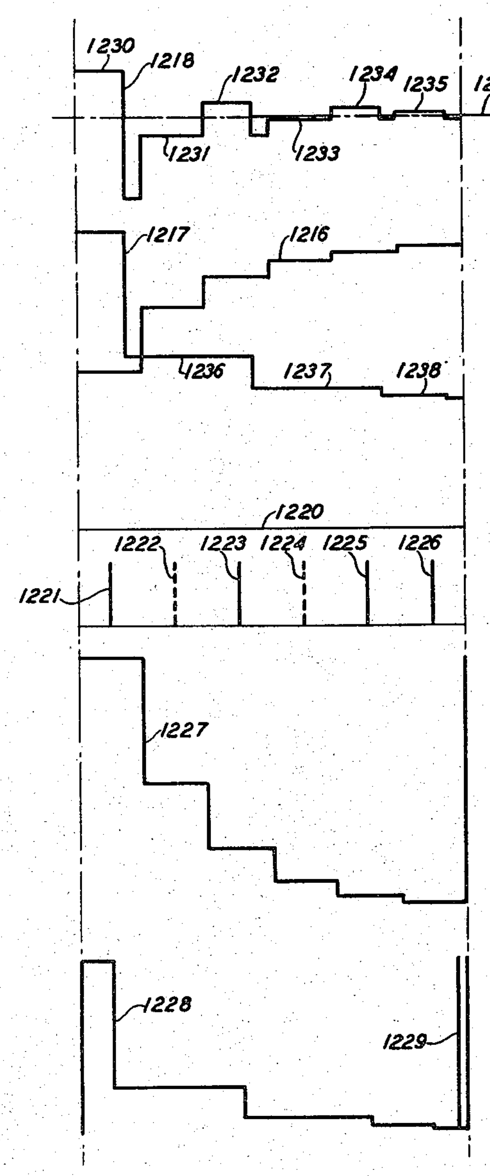
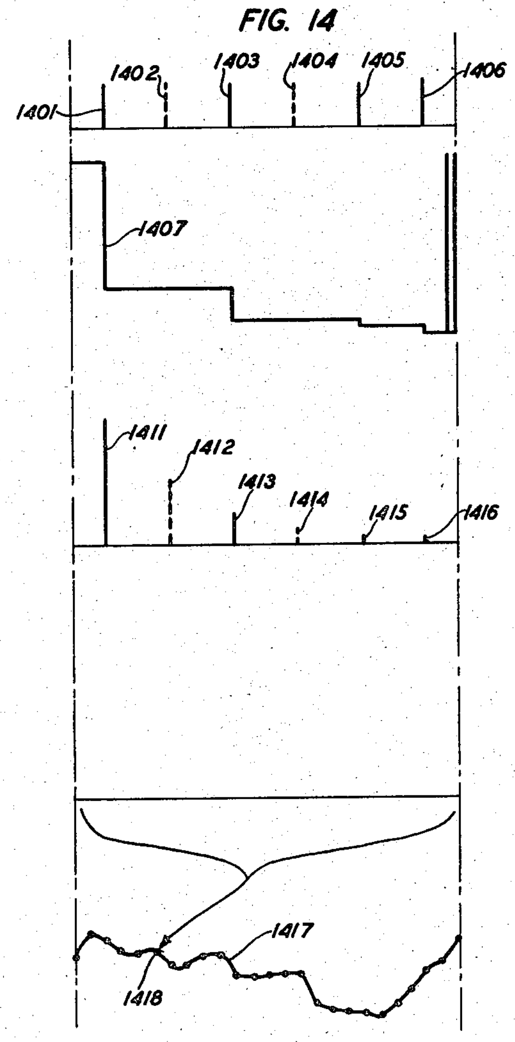


FIG. 14



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Patented Sept. 14, 1948 2,449,467

UNITED STATES PATENT OFFICE

2,449,467

COMMUNICATION SYSTEM EMPLOYING PULSE CODE MODULATION

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Application September 16, 1944, Serial No. 554,495

26 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 signal impulses of a plurality of different types or signaling conditions transmitted at high speed.

The 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 and at the same time the frequency band width required for the transmission of the signals is reduced to a minimum.

Another object of this invention is to provide improved and simplified methods and apparatus capable of transmitting and receiving signal impulses over a noisy transmission system and deriving therefrom signals having a high signal-to-noise ratio.

In the past, various communication systems have been proposed for improving the signal-to-noise ratio of the received signals. In one such system the amplitude of the signal wave to be transmitted is sampled at successive intervals and pulses transmitted having either their beginning or termination or both a function of the amplitude of the complex wave. While such systems may secure an improvement in the signal-to-noise ratio they require either a wide frequency band or a long time interval or both for the transmission of the pulses representing a single amplitude.

Other systems have been proposed in which a group of pulses are transmitted over a plurality of separate or individual transmission paths. Such an arrangement is complicated and cumbersome and requires a plurality of transmission paths for the transmission of each of the complex waves to be transmitted. Furthermore, in most of the systems in the prior art, it is necessary to count a large number of pulses in order to determine the character and position of each pulse of each group of pulses to be transmitted representative of a given amplitude.

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.

It is another object of the present invention to provide improved apparatus for determining

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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.

Another object of the present invention is to transform a series of pulses representing the amplitude of a complex wave at a given instant of time into another pulse having an amplitude which is a function of the amplitude of the original complex wave.

Another object of this invention is to recombine a group of successive pulses of varying amplitude in such a manner as to reconstruct a wave form of substantially the same shape as the wave form transmitted.

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

Another feature of the present invention relates to apparatus and equipment for producing a wave form in the form of a plurality of steps of increasing or decreasing amplitude, the height or change in amplitude between successive steps being a predetermined fraction of the change in amplitude between the immediately preceding steps.

A feature of this invention resides in methods of and apparatus for varying the charge on a condenser by successively smaller amounts when the pulses of a code are received.

Still another feature of this invention relates to methods of and apparatus for varying the amplitudes of each of the pulses of a received pulse group so that the amplitude of each pulse is less than the amplitude of the previous pulse of the code group.

Another feature of the invention relates to a sampling apparatus for sampling a complex wave at frequent intervals of time.

In accordance with another feature of this invention an electrical quantity is obtained which is proportional to the amplitude of the complex wave at each time the complex wave is sampled.

Still another feature of this invention relates to apparatus for comparing said electrical quantity with the above-mentioned step-wave form and transmitting pulses under control of said apparatus for comparing said quantity and said step-wave form.

Another feature of this invention comprises equipment responsive to each impulse transmitted for causing a reduction in the magnitude of said electrical quantity by successively smaller amounts.

Other features of the invention relate to synchronizing and coordinating the various circuits and equipment at the transmitting terminal with each other and with the circuits and equipment of the receiving end so as to secure proper operation of the entire system.

A feature of the synchronizing and coordinating circuits and equipment relates to means for accurately pulsing, starting, or phasing an oscillator circuit for a timing circuit for each code or number group of the pulses transmitted.

Briefly, in accordance with the present invention, equipment is provided responsive to a synchronizing or controlling alternating current for generating a control pulse or a group of control 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 positive pulses interspersed with a series of very short negative pulses. The control pulses as well as the code element timing pulses are employed to generate a stepped-wave form of a plurality of steps, the change between each succeeding step of which is a predetermined fraction of the change between the previous steps.

Apparatus is also provided for sampling or deriving an electrical quantity which is a function of the amplitude of the complex wave to be transmitted under control of a control pulse generator. For each of the control pulses, a code element timing circuit generates a series of code element timing pulses, the step generator circuit generates a wave form having a plurality of steps as described above and the sampling circuit derives an electrical quantity having a magnitude related to the magnitude of the complex wave at the time of the control pulse. The magnitude of the electrical quantity is then compared with the magnitude of the stepped-wave form and if the electrical quantity exceeds the magnitude of the particular step at that time a pulse is transmitted over the transmission system. If the magnitude of the stepped-wave form exceeds the magnitude of the electrical quantity, no pulse is transmitted. Upon the transmission of a pulse the electrical quantity is reduced in magnitude. Thereafter the next step of the stepped-wave form is prepared for comparison with the remaining magnitude of the electrical quantity and the process repeated a predetermined number of times and the corresponding pulses transmitted. The amount subtracted from the electrical quantity as an incident to the transmission of each pulse is the total maximum value of the quantity multiplied by $1/A^n$ where A is a constant greater than 1 and usually 2 and n is the ordinal or digital number of the pulse transmitted. At the receiving station a control pulse generator, code element timing generator and a stepped-wave form generator similar to those of the transmitting station are also provided. In addition, decoding apparatus is provided in which the received pulses are employed to synthesize an electrical quantity having a magnitude similar to the magnitude of the electrical quantity of the transmission end of the system and then the complex wave is reconstructed from said electrical quantity.

Novel features of this invention which are believed to be characteristic thereof are set forth with particularity in the claims appended hereto. The invention itself, however, both as to its organization and method of operation together with other objects and features thereof may be best understood from the following description when read with reference to the accompanying drawings in which:

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

Figs. 3 to 10 when positioned as shown in Fig. 16 show in detail the various circuits and equipment of an exemplary communication system embodying the present invention; of these Figs. 3 and 5 may be common to all channels at a transmitting terminal, and 8 and 9 are common to all channels at a receiving terminal;

Figs. 11 and 12 show curves or wave forms of the voltages or currents at various places in the system at the transmitting end or station;

Figs. 13 and 14 show similar curves and wave forms at the receiving station;

Fig. 15 shows the manner in which Figs. 1 and 2 are placed adjacent each other;

Fig. 16 shows the manner in which Figs. 3 through 10 should be placed adjacent each other; and

Fig. 17 shows the manner in which Figs. 11 through 14 should be placed adjacent each other.

Figs. 1 and 2 show in schematic form the various circuit elements and apparatus and the manner in which they cooperate to form an exemplary system embodying the present invention. Fig. 1 shows the apparatus and circuits at one station while Fig. 2 shows similar apparatus and circuits at a second station. As shown in Figs. 1 and 2, two transmission paths or channels are provided in each direction.

It will be obvious to persons skilled in the art that additional channels in either or both directions may be provided between each of these stations. It will also be obvious to persons skilled in the art that additional stations or terminals may be provided and similar transmission paths or channels extended between any or all of the various stations.

As shown in Figs. 1 and 2, lines 6 and 9 represent two communication paths between the two stations. Signals are transmitted over line 6 from the station shown in Fig. 1 to the station shown in Fig. 2. Signals are transmitted over line 9 from the station shown in Fig. 2 to the station shown in Fig. 1. These lines 6 and 9 represent communication paths between the two stations which may be of any suitable type for the transmission or conveyance of electrical signaling pulses of the proper frequency range. These paths may be used independently of each other or in pairs to provide two-way circuits. These paths are illustrated in Figs. 1 and 2 by a single line. Persons skilled in the art, however, will readily understand that these lines represent any and all types of communication paths and combinations thereof including open wire lines, cable conductors, twisted pairs, channels of carrier current systems, coaxial lines, wave guides, and radio channels and may also include time division multiplex channels. Furthermore these transmission paths may include suitable amplifiers, filters, predistortion networks, equalizing networks, gain control networks and circuits, phase control circuits and networks, repeaters, repeater stations, as well as signal operated switching devices which control the direction of transmission. In addition, when the transmission path is over a coaxial cable the transmission system may include any or all the features disclosed in or referred to in United States Patents 2,343,568 granted to L. W. Morrison, Jr., on March 7, 1944, 2,212,240 granted August 20, 1940, to Lalande et al.; and 2,095,360 granted October 12, 1937, to Green. These features may also be employed for other types of conductors when desirable. These channels may also include regenerative repeaters as well as the other terminal equipment associated with each of the respective types of transmission paths suitable for terminating and interconnecting the various types of transmission lines so that they will each cooperate with the adjacent sections to form a continuous transmission channel between the two stations. In addition to lines 6 and 9, two radio channels are shown in Figs. 1 and 2. Transmitting antenna 7 and receiving antenna 8 represent one of the radio channels, while wave guide 13 and horn or radiator 12 and the horn 11 and wave guide 14 illustrate a second radio channel between these stations. A typical example of a radio channel including radio relay repeater stations suitable for the transmission of pulses of the type employed in the exemplary system described herein is described in detail in a series of papers published in the Proceedings of the Institute of Radio Engineers for November 1934 entitled "An experimental television system," part 1 of which is entitled "Introduction" which is by E. W. Engstrom; part 2 of which is entitled "The transmitter" and is by Kell, Bedford and Trainer; part 3 of which is entitled "The receivers" and is by Holmes, Carlson and Tolson; and part 4 which is entitled "The radio relay link for television signals" and is by Young. Another sutable type of radio amplifier repeater and transmitter is described in detail in an article entitled "High gain amplifier for 150 megacycles" by Rodwin and Klenk published in the Proceedings of the Institute of Radio Engineers for June 1940. Typical wave guide and horn or radiator structures are described in United States Patent 2,206,923 granted to Southworth July 9, 1940. The foregoing publications and patent are hereby made a part of the present application to the same extent as though set forth in full herein.

In addition a synchronizing path or channel 5 is shown extending between the two stations shown in Figs. 1 and 2. This control path or channel may be similar to the other transmission paths between the stations. Furthermore, if it is so desired the synchronizing signals or the control frequency may be transmitted over one more or more of the other transmission paths extending between the two stations. Inasmuch as there are numerous types of synchronizing apparatus in the art which will operate over the same transmission paths as employed for the transmission of communication signals and since the operation of this type of equipment is well-known and understood by persons skilled in the art, it is considered unnecessary to further expand the present disclosure to show details of a typical system of this type. It is understood, of course, that such equipment will cooperate with the various circuits of the present invention and may be provided when it is so desired.

Each of the stations is provided with certain control equipment which may be common to all of the circuits terminating at that station or it may be common to a plurality of the circuits terminating thereat. Of course, this common equipment may be provided for each of the individual circuits if it is so desired as is well understood by persons skilled in the art. However, in the systems

shown in Figs. 1 and 2 the control circuits and equipment are shown at the top of these figures and are common to all of the channels shown to terminate at each of the respective stations.

The common equipment at station 1 comprises a control oscillator 110 which may be of any suitable type, as for example, the types described in detail in any one or more of the following patents: 1,476,721, Martin, December 11, 1923; 1,660,389, Matte, February 28, 1928; 1,684,455, Nyquist, September 18, 1928, and 1,740,491, Affel, December 24, 1929.

The output of the control oscillator is coupled to control a control pulse generator 111. The output of this generator extends to receiving and monitoring equipment as shown in the drawing and also to delay network 112. Delay network 112 may be any suitable type of delay network as, for example, one or more sections of one or more of the types disclosed in United States Patent 1,770,422, granted July 15, 1930, to Nyquist. The output of delay network 112 extends to sampling circuits 122 and 132 and also to a code element timing circuit 113. The output of the code element timing circuit extends to the coding and comparing circuits 123 and 133 and also to a step-wave generator 114. The output of the step-wave generator extends to the sampling circuits 122 and 132 and also to the coding circuits 123 and 133.

Similar common equipment comprising a control oscillator 210, control pulse generator 211, delay network 212, code element timing circuit 213 and a step-wave generator 214 are provided at the station shown in Fig. 2.

In addition to the control oscillator 110 and 210 respectively at each of the control stations a master oscillator 10 is shown in Fig. 1. This master oscillator may be located at either of the stations 1 or 2 and when so located at either of these stations, may replace the control oscillator 110 or 210 at either of these stations. However, the master oscillator is frequently located at some central point and provides a control frequency for an entire nationwide system or for some smaller divisions or sections of a large system. Typical oscillators and standard frequency systems suitable for use as a master oscillator or source of control frequency are disclosed in United States Patents 1,788,533, Marrison, January 13, 1931; 1,931,873, Marrison, October 24, 1933; 2,087,326, Marrison, July 20, 1937; 2,163,403, Meacham, June 20, 1939; and 2,275,452, Meacham, March 10, 1942.

All of the patents referred to above are hereby made a part of the present application as if fully included herein.

The sources of signals 120 and 130 in Fig. 1 and 220 and 230 in Fig. 2 are illustrated in the drawing by microphones. It will be apparent to persons skilled in the art that other suitable sources of signals may be employed such as picture transmission systems, television systems, mechanical vibration pick-ups, photoelectric devices, piezoelectric devices, etc.

Each of these sources is connected to the respective terminal equipments 121, 131, 221 and 231. This terminal equipment represents all of the equipment connected between the sources or microphone and transmission circuits and equipment for coding the signals to be transmitted as will be described hereinafter. This terminal equipment may include one or more of the following typical types of apparatus including amplifiers, transmission lines, switching equipment of any suitable type such as manually controlled switching equipment at a manual central office, automatic or machine or dial switching equipment such as employed in an automatic central office as well as phase control apparatus, equalizing apparatus, voice controlled switching apparatus, etc. This terminal equipment may also include toll line facilities and toll line switching equipment. When the terminal equipment 121, 131, 221 or 231 includes switching equipment the transmission circuits described hereinafter in detail embodying the present invention function as trunk circuits.

The signals from the devices 120, 130, 220 and 230 then extend to sampling circuits 122, 132, 222 and 232 respectively. Associated with each of the sampling circuits is a comparing or coding circuit 123, 133, 223 and 233. From the comparing coding circuit the signals are transmitted through the associated high frequency transmitters to the other station. After the signals have been received at these stations they are transmitted through a phase or time delay circuit 114, 153, 244 or 253 which may be constructed of a suitable number of network sections of a suitable frequency range of one or more of the types of the above-identified Patent 1,770,422 granted to Nyquist. As will be readily understood by persons skilled in the art, it is necessary that the incoming signals be maintained in a predetermined phase relation with the common equipment at the receiving stations so as to be properly decoded and translated so that the original complex wave may be reconstructed. It is, of course, possible to provide the phase or delay equipment at each of the stations for each of the transmitting and receiving terminals located thereat. It is also possible to provide such equipment in the synchronizing channel. However, as shown in Figs. 1 and 2 the phase control equipment has been provided at the receiving terminals of the channels terminating at the respective stations. This arrangement has the advantage that the phase control equipment may be adjusted to compensate for the delayed time of each of the respective channels so that it is possible to employ common control equipment at each of the stations for the operation of each of the channels terminating thereat. After passing through the receiving and phase control equipment at the respective stations, the signals are decoded by the respective decoding circuits 142, 152, 242 and 252 and conveyed to the respective terminal equipment 141, 151, 241 and 251 and then to the receiving or recording devices 140, 150, 240, or 250, respectively. The terminal equipment 141 and 151, 241 and 251 may include any of the types of apparatus or equipment described above with reference to the terminal equipment 121, 131, 221 or 231.

Inasmuch as the circuits individual to each of the channels all operate in substantially the same manner the circuits of a single channel only have been shown and described herein in detail. It must be understood, however, that similar circuits are duplicated for each of the additional channels extending between any of the stations of the system.

A control pulse generator 111 is provided at the transmitting station and connected to the output of the control oscillator 110 or the master oscillator 10. The control pulse generator 111 is arranged to generate control pulses of both positive and negative polarity in response to the alternating current or voltage applied thereto from the control oscillator 110 or the master oscillator 10. In the exemplary embodiment of the invention set forth herein a control pulse generator 111 simultaneously generates a positive and a negative control pulse for each cycle of the alternating current applied thereto. The negative control pulse from the control pulse generator 111 is transmitted through a delay network 112 which in the exemplary embodiment set forth herein consists of a time or phase delay network comprising impedance elements such as resistances, inductances, and capicities as pointed out above. The output of the delay network 112 is connected to a code element timing circuit 113, a step generator 114 and a sampling circuit 122.

In response to each of the control pulses applied to the code element generator or timing circuit 113 a series of code element timing pulses is generated. Each series of code element timing pulses comprises a group of positive pulses interspersed with an equal number of negative pulses. A positive pulse and a negative pulse are generated by the code element timing circuit for each pulse of each code group of the signalling pulses as will appear hereinafter. The output of the code element timing circuit is connected to the step generator 114 and also to comparing and coding circuits 123 and 133. Step generator 114 is employed to generate an output wave in the form of a plurality of steps, the height of each succeeding step being a predetermined fraction of the height of the previous step. In the exemplary embodiment of the present invention the height of each succeeding step is one-half the height of the previous step. Step generator 114 generates a step for each of the negative pulses applied thereto by the code element timing circuit 113. In addition the entire step wave pattern from the step generator 114 is generated for each of the control pulses applied thereto from the control pulse generator 111 through the delay network 112. The output of the step generator 114 is connected to sampling circuits 122 and 132, to coding and comparing circuits 123 and 133, to the decoding circuits 142 and 152, and to monitoring equipment 125, 135, 145 and 155. The outputs of the comparing and coding circiuts 123 and 133 are connected to transmitting amplifier 124 or radio transmitter 134 as well as to the monitoring equipment 125 and 135 and the sampling circuits 122 and 132.

Briefly the operation of the system is as follows. Assume for example that the input speech, music or picture signal from microphone or other device 120 has a wave form such as illustrated by curve 1101 of Fig. 11. Assume further that the frequency of the master oscillator 10 is such that a control pulse is generated by the control pulse generator 111 at the times corresponding to each of the large dots 1102 on curve 1101. At each of these times a control pulse is transmitted through the delay network 112 to the sampling circuit 122 where some electrical quantity such as, the charge on a condenser is made proportional to the instantaneous amplitude of the complex wave at that time. In addition, the code element timing circuit and the step generator are set into operation. The outputs of the sampling circuit and the step generator are compared in the comparing and coding circuits 123. If the sample obtained from the complex wave as described above is greater than the amplitude of the step wave from step generator 114 at the time of the first positive pulse from the code element timing circuit 113, a signalling pulse is transmitted from the comparing and coding circuit 123. If the amplitude of the wave from the step-wave generator is greater than the amplitude of the sample at this time, i. e., is greater than the charge of the condenser referred to above, no signalling pulse will be transmitted at this time. Assuming for purposes of illustration that the charge or potential on the condenser in the sampling circuit is greater than the amplitude of the step wave when the first positive pulse is transmitted from the code element timing circuit, then the pulse will be transmitted from the comparing and coding circuit 123. This pulse is transmitted through the transmitting amplifier 124 over line 6 to the receiving station. This pulse is also transmitted to the monitoring equipment 125 and also to the sampling circuit 122. When this pulse arrives at the sampling circuit 122 it has been delayed somewhat by the amplifiers and if necessary other delay equipment, so that it will not interfere with the pulse actually transmitted from amplifier 124 over line 6. When this transmitted pulse arrives at the sampling circuit 122, it causes the charge or potential of the condenser therein to be reduced by an amount controlled by the amplitude of the step wave generated by the step wave generator 114. As assumed above, when the step wave will have its first amplitude, the charge or potential of the condenser in the sampling circuit will be reduced by an amount equivalent to substantially half of the maximum charge which may be applied to that condenser by a signal wave having its maximum possible amplitude at the time of sampling.

Thereafter the code element timing circuit 113 will transmit a negative pulse to the step generator which will cause the output wave form to assume its next value. This value will then be compared with the remaining charge or potential on the condenser of the sampling circuit and another pulse transmitted or not, depending upon whether or not the charge on the condenser in the sampling circuit is greater or less than the magnitude of the second step from the step generator. Assuming for purposes of illustration that the potential of the second step of the step generator is greater than the charge on the condenser in sampling circuit 123, no pulse would be transmitted. Consequently, the charge upon the condenser in the sampling circuit will not be reduced.

A short interval of time later another negative pulse will be transmitted from the code element timing circuit 113 and cause the output of the step generator 114 to assume the value of the next step. This is again compared with the potential on the condenser in the sampling circuit in order to control the transmission of the next pulse. The above-described cycle of operation is then repeated a predetermined number of times, depending upon the number of code elements employed to represent each of the amplitudes sampled by the sampling circuit. In an exemplary embodiment of the invention described herein it has been assumed that six code pulses will be sufficient to represent the various amplitudes of the complex wave.

With the six code pulses it is possible to represent 64 different magnitudes of the instantaneous amplitude of the complex wave. If five code pulses are employed, 32 different amplitudes may be represented by the different code combinations. If it is desired to more accurately determine and represent the instantaneous amplitude of the complex wave form more code pulses may be employed. For example, if seven code pulses are employed 128 different amplitudes may be represented. In other words 2^n different amplitudes may be represented by the permutations of n pulses of two different types, i. e., current or no current. It will be readily understood by persons skilled in the art that in order to change the number of code elements representing each amplitude it is only necessary to change the number of pulses generated by the code element timing circuit 113 in response to each of the control pulses transmitted through the delay network 112.

After all of the pulses of a given code group are transmitted another control pulse from the control pulse generator 111 will cause the equipment to sample the complex wave form at a succeeding interval of time and the above process is repeated. The interval of time between samples of the complex wave, together with the number of different amplitudes representing each of the instantaneous amplitudes determine the accuracy and fidelity of the reproduction of the complex wave form at the receiving station as will be readily apparent to persons skilled in the art.

Monitoring equipment 125 is provided at the transmitting station and is connected to the control pulse generator 111, step generator 114, and the output of the comparing and coding circuit 123 and is arranged to decode each group of code pulses and generate a pulse having an amplitude proportional to the instantaneous amplitude represented by the code group of pulses transmitted. Each of these pulses of varying amplitude generated in the monitoring circuit is applied to a low pass filter and then to some receiving device or indicator 126 so that the operation of the system may be monitored at the transmitting station. A monitoring circuit is shown in Fig. 1 for each channel. It will be apparent to persons skilled in the art that the monitor circuit may and usually will be common to a number of the channels and connected to any desired channel by keys, a plug and jack or other suitable equipment.

The station shown in Fig. 2 is similarly provided with a control pulse generator 211 which generates a pulse in response to each oscillation received over channel 5 and from oscillator 210. However, in the event that channel 5 becomes inoperative, the control pulse generator 211 will still be controlled by oscillator 210. Consequently, it may be possible to operate the system for a considerable period of time, without receiving a synchronizing or controlling frequency over channel 5.

The receiving station is likewise provided with a delay network 212, code element timing circuit 213, and step-wave generator 214 which operates in substantially the same manner as described above with reference to a transmitting station. The output of the step generator 214 is connected to the decoding circuit 242 to which is also applied the received signals after being amplified by amplifier 243. The decoding circuit 242 changes the constant amplitude of each of the received pulse groups into pulses of varying amplitude depending upon the amplitude of the step wave at the time the individual pulses of the group are received. The pulses of varying amplitude are then applied to a low pass filter where the complex wave form is thereupon reconstructed or regenerated. The output of this filter is then connected to terminal equipment 241 where it is transmitted to the receiving device 240. Terminal equipment 241 may include any or all of the equipment mentioned above with reference to terminal equipment 121. It will be readily understood by persons skilled in the art that terminal equipment 121 and 241 may each include any of the different types of equipment referred to above but that both of these devices do not necessarily have to include the same types of equipment but may include such equipment.

Monitoring equipment 245 is provided at the receiving station and enables the attendants to check the operation of the receiving apparatus. This equipment as shown in Fig. 2 is individual to the transmission path 6. It may be common to all the paths terminating at the station of Fig. 2 in which case it would be switched to the transmitting or receiving end of any path over which it was desired to observe the transmission.

Reference will now be made to Figs. 3 through 10 inclusive when arranged as shown in Fig. 16 which set forth in detail the various circuits and apparatus which cooperate to form a typical exemplary communication system embodying the present invention.

Figs. 3 through 7 inclusive illustrate in detail the common equipment employed at one station at which it is assumed the complex wave form is applied to the system. This station will frequently be called a transmitting station hereinafter. Figs. 8, 9 and 10 show the equipment at a second station at which the complex wave form is reconstructed and delivered to utilization circuits and equipment. This station will be frequently called hereinafter a receiving station. In addition, Figs. 3 through 10 inclusive show only a single one way communication path and the equipment thereof in addition to the equipment common to a plurality of paths. Figs. 3 and 5 show details of circuits at the transmitting station which are common to a number of transmission paths and Figs. 8 and 9 show similar circuits at the receiving station. The other figures show the equipment which is individual to each transmission path. It will be readily appreciated by persons skilled in the art that to provide additional communication paths in either direction between two stations, it is only necessary to provide additional equipment similar to the equipment shown in Figs. 4, 6, 7 and 10 which is indivdual to each of the transmission paths.

In order to better understand the operation of the system the common equipment shown on the top of Figs. 1 and 2 in diagrammatic form will be described first.

Fig. 5 illustrates a master oscillator 510 and the second oscillator 525. If the master oscillator 510 is located at the transmitting station the details of which are illustrated in Figs. 3, 4, 5, 6 and 7 the local oscillator 525 may be dispensed with. However, in case the master oscillator 510 is located at some other station or is a master frequency standard for a large number of stations, systems, or for the entire country, both oscillator 510 and the local oscillator 525 will usually be employed. Master oscillator 510 may be of any suitable type such as the type disclosed in the above-identified Meacham, Marrison or Morrison patents. The local oscillator 525 will then incorporate some control apparatus for maintaining its frequency in synchronism with the frequency from the master oscillator 510 similar to the equipment described in detail in the above-identified patents. Oscillator 525 is connected over a synchronizing line 580 which is shown in Fig. 5 as a coaxial line and extends to the receiving station shown in Figs. 8, 9 and 10. Here the coaxial line 580 terminates in a local oscillator 810 which is similar to the oscillator 525. While the synchronizing line 580 is shown as a coaxial line, persons skilled in the art will readily understand that any suitable type of transmission path may be employed which is capable of transmitting the synchronizing frequency employed.

Pulse generator

The local oscillator 525 or the master oscillator 510 is connected to a multi-vibrator circuit comprising tube 511. The multi-vibrator circuit 511 operates to generate square waves of the same frequency as received from oscillator 525 or 510. Multi-vibrator circuits are well known in the art. Typical multi-vibrator circuits suitable for use in the present system are described in United States Patents 1,744,935 granted to Van der Pol January 28, 1930, and 2,022,969 granted to Meacham on December 3, 1935, and in an article by Hull and Clapp published in the Proceedings of the Institute of Radio Engineers for February 1929, pages 252 to 271. See also section 4–9 "Multivibrator" on page 182 of Ultra-High-Frequency Techniques by Brainerd, Kochler, Reich and Woodruff. The output of the multi-vibrator 510 is coupled through a condenser 512 and a resistance 513 to amplifier tube 514.

Condenser 512 is made variable so that it, together with resistance 513 may be employed to control the length of the synchronizing pulses derived from multi-vibrator circuit 511. If the time constant of condenser 512 and resistance 513 is large the output pulse will be relatively long, whereas if the time constant of condenser 512 and resistance 513 is small the output pulse will be short. In a typical example of the present system the values of condenser 512 and resistance 513 were selected to produce an output of approximately two microseconds.

Condenser 512 and resistance 513 are coupled to the control grid of amplifier 514. The output of the amplifier tube 514 is in turn coupled to tubes 515 and 516. Tubes 514, 515 and 516 are amplifier tubes which are overloaded by the magnitude of the pulse applied to them so that these tubes tend to limit the magnitude of the pulse repeated through them and at the same time tend to make it square in wave shape. Amplifiers of this type are sometimes called "limiters" and at other times "clipping" amplifiers because they limit, clip off or suppress the top portion of the waves applied to them. A single stage "limiter" is shown in Fig. 8—6 on page 282 and described on page 283 of Ultra-High Frequency Techniques by Brainerd, Kochler, Reich, and Woodruff, first published July 1942 by D. Van Nostrand Company, Incorporated.

The output of tube 516 is coupled to a power tube 517 which is employed to supply sufficient power for the output pulses of the circuit so that they may be employed to control the other circuits of the system. The output tube 517 is arranged to supply both positive and negative pulses. Negative pulses are obtained from the plate of tube 517, while positive pulses are obtained from its cathode as shown in Fig. 5.

As will be readily appreciated by persons skilled in the art, in case a large number of circuits are supplied from pulse generator shown in Fig. 5, additional output stages may be connected in parallel with tube 517, may have their input circuits connected in parallel with the input circuit of tube 517, or may be driven from this tube as is well understood and frequently employed.

The negative pulses from the plate of tube 517 pass through a delay network 522 where they are delayed slightly in time with respect to positive pulses 521. The purpose of this delay will be explained hereinafter. Delay network 522 will be of any suitable type employing reactive elements in a manner well understood in the art and pointed out above. The output of the pulse generator shown in Fig. 5 is diagrammatically indicated by the small curve 521 for the positive pulses and 523 for the negative pulses in order to facilitate the reading and understanding of the drawing.

In order to further facilitate the understanding of the operation system reference will also be made to Figs. 11, 12, 13 and 14 when arranged as shown in Fig. 17. Referring now to Fig. 11, curve 1101 represents a complex wave form of a type suitable for transmission over the system described herein. As will be described hereinafter the magnitude or amplitude of this wave form is sampled or measured at frequently recurring intervals of time. For purposes of illustration the operation of the system will be described in detail for one such measurement which is assumed to be made at the point 1103.

Vertical lines 1105 in the next set of curves represent the positive pulses 521 supplied by the pulse generator shown in Fig. 5. Likewise, the vertical lines 1104 represent the negative pulses generated by the pulse generator shown in Fig. 5. As shown in Fig. 11 pulses 1104 are delayed slightly and consequently follow pulses 1105. This is apparent in Fig. 11 when it is assumed that time increases in a positive direction to the right.

It is further assumed in the exemplary system described in detail herein that the samples of the complex waves are obtained at a rate of 8,000 times a second. Persons skilled in the art will understand that any other suitable frequency may be employed so long as this frequency is appreciably higher than the highest frequency component of the complex wave necessary or desirable to transmit to the distant station. In other words, the frequency of oscillators 510 and 525 are either 8,000 cycles a second or else frequency changing apparatus is connected between them and the multi-vibrator 511 in a manner understood in the art so that multi-vibrator 511 is supplied with an alternating current of 8,000 cycles per second. In other words, pulses 1105 as well as the slightly delayed pulses 1104 are supplied from the pulse generator in Fig. 5 at the rate of 8,000 per second. Consequently, there are 125 mircoseconds between pulses 1105. Similarly a period of 125 microseconds elapses between the pulses 1104.

The negative pulses are supplied to an amplifier tube 310 shown in Fig. 3 where they are amplified and changed into the positive pulses due to the inversion of the amplifier tube 310. Tube 310 is shown as a double triode tube. However, it is noted that both sections are connected in parallel so that this tube merely serves as a single triode tube. As will be readily understood by persons skilled in the art, this tube may be replaced by any suitable triode tube having a desired output current or power capability. This amplifier also may comprise any multielement tube operated either as a triode with various of the elements connected together or in any other suitable manner.

Code element timing circuit

The output of tube 310 is connected to code element timing circuit comprising tubes 311, 319, 320 and 321. The left-hand section of tube 311 is employed to shock-excite the resonant circuit comprising condenser 312 and inductance 313 connected in parallel in the cathode circuit of the left-hand section tube 311. The bias conditions applied to the left-hand section of tube 311 are such that the tube is blocked or non-conducting at all times except when the positive pulse from tube 310 is applied to its grid. At these times the left-hand section of tube 311 forms a low impedance path for supplying current and energy to the oscillating circuit connected in its cathode circuit. At all other times the anode-cathode circuit of tube 311 is of such a high impedance that it does not materially affect the oscillations of the resonant circuit comprising elements 312 and 313. The application of a positive pulse to the grid of tube 311 thus sets the resonant circuit described above into oscillation. The wave form of such oscillations is shown by curve 1106 in Fig. 11.

As shown by curve 1106 one suitable type of adjustment for the resonant circuit is such that substantially six complete oscillations take place between the positive synchronizing pulses applied to the grid of the left-hand section of tube 311.

In other words, in each period between the synchronizing pulses there is generated one cycle or oscillation for each code pulse of the group of code pulses. If only five pulses are required to represent the various amplitudes of each sample of the complex wave then the tuning of the resonant circuit comprising condenser 312 and inductance would be varied to generate five cycles or oscillations between synchronizing pulses.

As shown by curve 1106 slightly more than six complete oscillations of the resonant circuit take place but the synchronizing pulse causes the circuit to start oscillating from substantially the same point and with the same phase each time it is received. By supplying energy to the oscillating circuit when the current through the coil is small and by utilizing the low impedance of the cathode circuit, transients are maintained small and quickly damped out. Transients do not, therefore, materially affect the frequency or amplitude of the oscillations and at the same time the oscillations are maintained in proper phase.

The cathode of the left-hand section of tube 311 is connected to the grid of the right-hand section of this tube. The output impedance of the right-hand section comprises a cathode resistor 314 which is of such a value that the right-hand section of tube 311 acts as a so-called "cathode follower" and thus presents an extremely high impedance to the resonant circuit comprising elements 312 and 313. Consequently, the operation of the right-hand section of tube 311 does not materially alter or interfere with the operation of the resonant circuit. Such properties and operation of "cathode followers" are well-known to persons skilled in the art. (See "The cathode follower" by C. E. Lockhart, parts I, II and III, published in Electronic Engineering, December 1942, February 1943, and June 1943, respectively.)

The cathode of right-hand section of tube 311 is coupled through a resistance and capacity network to the grid of tube 319. Capacity 316 and resistance 315 are employed in the coupling circuit in order to properly control the wave shape of the pulses transmitted to and repeated by the tube 319. Resistances 314, 315 and 335 together with the position of potentiometer 318 control or determine the bias of the grid of tube 319. Condenser 316 is connected across resistance 315 to compensate for the effect of the input capacitance of tube 319, thus causing the potential of the grid to rise substantially as fast as the applied potential, i. e., the cathode potential of the right-hand section of tube 311. The optimum value of condenser 316 is the value of the input capacitance of tube 319 multiplied by the ratio of resistance 315 to resistance 335. It should be noted that the potentiometer 318 is connected between the negative source of bias voltage and ground.

The output of tube 319 is similarly connected to tube 320 and the output of this tube in turn, connected to tube 321. Tubes 319 and 320 are adjusted to operate as overloaded amplifiers so that they will limit the amplitude of the output pulse and at the same time cause these pulses to approach a square wave form. Tube 321 is a power tube for supplying sufficient output power to operate the other circuits as will be described hereinafter. In this case as in the case of the output of the pulse generator, sufficient additional output tubes may be provided parallel with or supplied by tube 321 to provide the necessary output currents and voltages as well as to isolate the various different circuits one from another, as may be required.

The amplifier tubes 319, 320 and 321 have their circuits and bias potentials so adjusted that a wave form approaching that illustrated by curve or broken line 1107 appears in the output from the tube 321. Both the positive and negative portions of this wave form as shown in the drawing are substantially of the same duration. Persons skilled in the art will at once realize that it is not necessary that both of these portions of the wave be of equal or substantially equal duration but may and usually will be of different duration to secure optimum operation. Furthermore, these waves are shown to be rectangular in form, as are other waves in the drawing. In practice, the waves are rounded to a greater or lesser extent. Inasmuch as typical actual wave forms approach the wave forms shown in the drawing and would not further aid in an appreciable manner the understanding of this invention the actual waves are represented by the forms shown in the drawing which are much easier to draw and adequately represent the operation of the system. The output of tube 321 passes through condenser 332 to grid of the right-hand section tube 327 and also through condenser 721 to the grid of tube 715. The time constants of condenser 332 and resistance 334 and of condenser 721 and resistance 725 is very short so that these condensers act to differentiate the output wave form 1107 and apply very short pulses as illustrated in Fig. 11 by 1108 and 1109 to the grids of these tubes. The function of these pulses when applied to grids of the respective tubes will be described hereinafter. From an examination of Fig. 11 it is apparent that six positive pulses 1108 and six negative pulses 1109 interspersed between the positive pulses are generated by the pulse generating circuit for each synchronizing pulse 1104 applied to the code element timing circuit. In other words, a negative pulse and a positive pulse is generated by the code element timing circuit for each complete oscillation of the resonant circuit comprising condenser 312 and inductance 313. As will be explained hereinafter the negative pulses 1109 are employed to control certain other tube circuits necessary for the proper operation of the system while the positive pulses 1108 are employed to cause a transmission of the code signaling pulses.

Step wave generator

The amplified synchronizing pulse from tube 310 is also applied to the grids of both sections of tube 323. When the delayed synchronizing pulse, which is positive when applied to the left-hand section of tube 323, is supplied to the grid thereof, it causes this section to become conducting and to discharge condenser 330 so that the potential of the upper terminal of this condenser is reduced to a minimum value. It is not essential that the upper terminal of this condenser be reduced to ground potential at this time, the only requirement being that it be reduced to substantially the same predetermined potential each time that the synchronizing pulse is applied to the grid of the left-hand section of tube 323. When no synchronizing pulse is applied to the grid of this tube the grid is biased to such a value that the tube is blocked; i. e. the anode circuit is substantially cut off. Consequently, this tube has a high impedance at such times and does not materially alter or control the potential of the upper terminal of condenser 330.

When the synchronizing potential is applied to the grid of the right-hand section of tube 323 it likewise causes this tube to become conducting so that condenser 325 in the cathode circuit receives a relatively high positive charge. In other words, the cathode of the right-hand section of tube 323 attempts to follow the potential of the grid of this section and thus the upper terminal of condenser 325 is charged to a relatively high positive potential during the time the synchronizing pulse is applied to the grid of this tube. After the synchronizing pulse is over and until the next pulse arrives the grid bias of the right-hand section of tube 323 is of such a value that the tube is substantially cut off. Consequently, the right-hand section of this tube does not in any way affect, alter or control the potential of the upper terminal of condenser 325 at these times. The only time in which the right-hand section of tube 323 affects the charge on condenser 325 is during the time the synchronizing pulse is applied, as is described above.

After each synchronizing pulse, condenser 325 starts to discharge through resistance 324 connected in parallel with it. The discharge of condenser 325 through the resistance 324 is in accordance with the exponential curve as is well understood by persons skilled in the art. In other words, when the value of resistance 324 and the value of condenser 325 are both fixed as is the usual case, the curve of the potential of the upper terminal of condenser 325 against time follows a well-known exponential discharge curve. See section 123 beginning on page 453 of Principles of Electrical Engineering by Timbie and Bush, published by John Wiley and Sons, Inc., 1923 (First edition).

Although many suitable values for the relative magnitudes of condenser 325 and resistance 324 could be chosen to provide many different time constants suitable for operation in circuits described herein, in the exemplary embodiment employed in the present invention a suitable time constant for this network comprising condensers 325 and resistance 324 is chosen so that the potential on the upper terminal of condenser 325 will decrease to one-half its value during each of the pulse intervals. By reference to pulses 1109 and 1104 it is apparent that one of the pulses 1109 is generated a short interval of time after synchronizing pulse 1104 is received. Thereafter five additional pulses 1109 are generated before the next synchronizing pulse 1104 is generated. During the time interval between each one of the pulses 1109 the charge upon or the potential of the upper terminal of condenser 325 falls to a value equal to one-half of the value it had after the time the previous pulse was received.

The potential of the upper terminal of condenser 325 is applied to the grid of the left-hand section of tube 327. The cathode resistor 336 is connected in series with the cathode of this tube so that the grid of the left-hand section of tube 327 never becomes positive and never draws an appreciable amount of grid current. Consequently, the input impedance of the right-hand section of tube 327 remains high and does not materially interfere with the decay of the charge upon the upper terminal of condenser 325. The right-hand section of tube 327 is biased so that the anode-cathode path of this section normally conducts current. Consequently, there is a relatively high potential drop appearing across the anode resistor 328 common to both sections of tube 327. This potential drop across resistor 328 is coupled to the grid of the left-hand section of tube 329 through a condenser and resistance network such that the potential of the grid of the left-hand section of tube 329 accurately follows the potential of the anodes of tube 327.

As indicated in Fig. 11 a short interval of time after synchronizing pulse 1104 is over, the first of the code element timing pulses 1109 is applied to the grid of the right-hand section of tube 327 through the coupling condenser 332. As indicated in Fig. 11 these pulses will be negative and tend to cut off the right-hand section of tube 327. Consequently, the current flowing in the anode-cathode circuit of this tube is reduced to a very low value. As a result the potential drop across the anode resistance 328 decreases so that the voltage of the anodes of tube 327 rises until the left-hand section of tube 327 starts to draw an appreciable amount of current of a value depending upon the grid potential which in turn is controlled by the potential of the upper terminal of condenser 325. Inasmuch as the first of the pulses 1109 follows the synchronizing pulse 1104 with little or no delay, the potential of the upper terminal of condenser 325 will be at a maximum at this time. This means that the potential of the anodes of tube 327 will rise only a small amount because the grid of the left-hand section is maintained at a high positive potential with respect to ground. This means that only a very small pulse will be applied to the grid of the left-hand section of tube 329. Consequently, little or no charge will be stored upon the upper terminal of condenser 330 at this time. At the end of the first negative timing pulse the right-hand section of tube 327 again becomes conducting and the potential drop across resistance 328 increases so that tube 329 will again become nonconducting and the potential of the upper terminal of condenser 330 maintained at the value acquired during the first of the negative pulses 1109. Thereafter, as indicated in Fig. 11, the first of the positive pulses 1108 is applied to the grid of the right-hand section of tube 327. This grid, however, is already positive or sufficiently positive to cause the right-hand section of tube 327 to have a low impedance. Consequently, the application of a positive pulse to the grid of this section at this time will have substantially no effect upon the operation of the tubes or circuits. At the end of a second interval of time, which two intervals of time comprise a signal pulse interval, the second of the negative timing pulses 1109 will be received. This pulse again substantially cuts off the anode-cathode current of the right-hand section of tube 327. This time, however, the potential of the upper terminal of condenser 325 has fallen to substantially one-half the value it had when the first one of the timing pulses 1109 was applied to the grid of the right-hand section of tube 327.

Inasmuch as the potential of the grid of the left-hand section of tube 327 is now more negative than it was previously, this section of tube 327 will not draw as much anode current through the common anode resistance 328. Consequently, when the right-hand section of tubes 327 is cut off by the second of the timing pulses 1109, the potential across the common anode resistance 328 rises to a higher value than in the previous case. As a result, a pulse of substantially twice the amplitude of the previous case is applied to the grid of tube 329 causing this tube to conduct, charging the upper terminal of condenser 330 to a higher value. Thereafter, the above cycle of operation is repeated upon the reception of each of the succeeding negative timing pulses 1109 until another synchronizing pulse 1104 is received.

Curve 1113 of Fig. 11 shows the manner in which the potential of the upper terminal of condenser 325 decays during each period between successive synchronizing pulses 1104. The circles on curve 1113 represent the value of the potential upon this condenser at the time each of the negative timing pulses 1109 is applied to the grid of the right-hand section of tube 327.

Superimposed upon the curve 1113 is the step curve 1114 which shows the potential of the upper terminal of condenser 330, each one of the succeeding steps of curve 1114 being one-half the value of the previous step because the charge on the condenser 325 is one-half the value it had at the time the previous timing pulse was received.

In the foregoing detailed description it has been assumed and stated that the height of each of the steps is one-half of the previous step. The value of one-half is the optimum value but then the system will operate satisfactorily with other values between the steps. It is also unnecessary, but desirable, to maintain the same ratio between the various steps.

The zero axis for curve 1113 and the broken line 1114 forming the step wave form have not been shown in Fig. 11 because any suitable zero axis may be chosen. The zero axis is usually merely a reference point and adds or subtracts a given amount of fixed bias from the potentials of curves 1113 and 1114. Inasmuch as the relationship between the various portions of the curve control the operation of the circuit, this zero point or the added bias may be chosen by other factors such as tube and circuit constants. Furthermore, this constant bias may be removed by the means of a coupling condenser when the voltage derived from this step circuit is employed to control other circuits.

The upper terminal of condenser 330 is connected to the grid of the right-hand section of tube 329. A cathode resistor 337 is connected in series with the cathode of this section of tube 329 so that the grid of the right-hand section of tube 329 never becomes positive with respect to the cathode and the grid never draws current. Furthermore, the input or grid impedance of tube 329 is maintained at a high value so that the operation of the right-hand section of tube 329 does not in any way interfere with or alter the step voltage upon the upper terminal of condenser 330 as shown in curve 1114. The right-hand section of tube 329 then inverts and repeats this voltage to a power amplifier tube 331 which in turn repeats the step wave form as shown by graph 1115 to various of the other circuits employed in the exemplary system described herein.

Coding a complex wave form

It is assumed in Fig. 4 that 410 represents a microphone or other source of signals having a complex wave form. This source might include devices other than a microphone such as photoelectric tubes or vibration devices of any type or kind.

Device 410 in Fig. 4 represents a source of complex wave form such as illustrated by curve 1101 in Fig. 11. This wave form is transferred to or induced into an electrical system where it passes through equipment 411 which represents the terminal equipment shown in Fig. 1 and designated 121 therein. As pointed out above synchronizing pulses 1104 occur, in an exemplary embodiment of this invention, at the rate of 8,000 a second. These intervals are illustrated by the dots 1102 on curve 1101. For purposes of illustration the operation of the system will be described in transmitting code pulses representing the amplitude of the complex wave form at the time illustrated by the dot 1103 of Fig. 1. The complex wave form is applied to the grid circuit of the left-hand section of tube 412 which grid circuit continuously follows the input wave form and has a potential applied thereto which is a function of this wave form. The synchronizing pulse is applied to the grids of both sections of the amplifying tube 428. Both sections of tube 428 are connected in parallel so that this tube merely serves as a triode amplifier and like tube 310 may be replaced by a single triode or any other suitable amplifying tube capable of amplifying pulses of short duration. Tube 428 in amplifying the applied negative synchronizing pulse inverts its phase or polarity and causes a positive pulse to be applied to the anode of the left-hand section of tube 412. The resistor 414 is common to the anodes of tubes 428 and of the left-hand section of tube 412. The anodes of these tubes are, in turn, connected through the coupling condenser 415 to the grid of the right-hand section of tube 412. Thus, when the synchronizing pulse is applied to the tube 428 the potential of the anodes of these tubes rise to a high value dependent on the magnitude of the complex wave form at the time the pulse is applied to tube 428. An output pulse, having a magnitude which varies in accordance with amplitude of the complex wave form at the time of the synchronizing pulse, is applied to the grid of the right-hand section of tube 412 and causes the potential of the upper terminal of condenser 413 to rise to a value which is a function of the amplitude of the complex wave form at this time. When the synchronizing pulse is completed tube 428, which is normally biased so that it will be conducting except during the time of the application of the synchronizing pulse, becomes conductive and causes a large current to flow through the common resistance 414. A large current flowing through resistance 414 produces a large potential drop across this resistance and thus reduces the anode potential of the left-hand section of tube 412. Consequently, the grid of the right-hand section of tube 412 is maintained at a negative value thus blocking this section of tube 412. The right-hand section of tube 412 thereafter during the cycle of operations initiated by the synchronizing pulse produces no further effect upon the potential of the upper terminal of condenser 413.

The cathode of the right-hand section of tube 412 is connected to the grids of both sections of tube 419. Both sections of tube 419 are connected in parallel so that this tube may be replaced by a single three-element tube or any other suitable type of amplifying tube. Cathode resistor 429 is connected in series with the cathodes of tube 419 so that this tube acts as a cathode follower and repeats the potential of the upper terminal of condenser 413 without in any way disturbing or altering this potential.

The cathode of tube 419 is connected through network 420 to the grid of tube 422. The output of this tube is connected through a similar coupling network to the grid of one of the two comparing tubes 423 and 424. As shown in Fig. 4 the output circuits of tube 424 and 423 are connected together. The coupling network 420 is similar to the network comprising resistance 315 and condenser 316 described above and is capable of accurately coupling the various tube circuits together so that they function as linear amplifiers over a wide frequency range from substantially direct current to high frequencies the upper limit of which is determined by the characteristics of the tubes and circuit elements and the change in constants and reactance of the tube paths and circuit elements as the frequency further increases.

Thus the grid of tube 423 accurately follows changes in the potential of the upper terminal of condenser 413. However, the changes in potential of the grid of tube 423 may be greater than the changes of the upper terminal of condenser 413 due to the amplifying action of tube 422 which may more than compensate for the loss in the cathode follower tube 419. The gain of these tubes and circuits is so adjusted that the first step of the step wave form corresponds to one-half of the total maximum amplitude of the sample or amplitude of the complex wave form as it is applied to the comparison tubes or appears in the common cathode resistor. Furthermore, the operation of the amplifier tube 422 causes the voltage changes of the upper terminal of condenser 413 to be reversed when they are applied to the grid of tube 423. In other words, an increase in the potential of condenser 413 causes a decrease in the potential of the grid of tube 423. This in turn, causes a decrease in the anode current through tube 423 which in turn, causes or tends to cause an increase in the potential of the anode of tube 423.

The second tube 424 of the pair of tubes 423 and 424 has an anode resistor 430 in common with tube 423. Tube 424 has its grid circuit coupled through condenser 425 to the output of the step circuit described above. The time constant coupling condenser 425 and resistance 426 is sufficiently long so that the potential of the grid of tube 424 accurately follows the step wave form generated by the step wave generator described above. However, due to the inverter action of the amplifying right-hand section of tube 329 the step wave form is turned over and steps down as shown by curve 1115 instead of stepping up as shown in curve 1114 which represents the potential of upper terminal of condenser 330.

Thus the output currents of tubes 423 and 424 are combined and added together in resistance 430 to produce a combined output potential which is applied to grid of tube 710 through the coupling network 722. The operation of the two comparing tubes may be more fully understood from curves 1216, 1217 and 1218 of Fig. 12. Curve 1216 represents the potential at the anode of tube 424 resulting from the drop produced across resistance 430 due to the anode current flowing through tube 424. It should be noted that this potential is in the form of a step wave similar to step wave 1115, but again inverted or turned over due to the action of the tube 424. Curve 1217 represents the wave form of the potential at the anode of tube 423 resulting from the drop across the common resistor 430 due to the current flowing through the anode circuit of tube 423. Curve 1218 represents the sum of curves 1216 and 1217 when referred to a zero axis 1220. The zero axis 1220 may be any zero axis which may be arbitrarily chosen. However, in order to more clearly explain the operation of the circuit, a concrete example of a zero axis 1220 has been assumed.

The output of the two tubes 423 and 424 is connected through a coupling network 722 to the grid circuit of an amplifying tube 710. The amplifying tube 710 is of a type which will overload on small applied signals and thus tends to acts as a limiting amplifier. By means of potentiometer 723 the bias applied to the grid of tube 722 is adjusted to a value indicated in Fig. 12 by line 1219. When the potential applied to the grid of tube 710 is above the line 1219, tube 710 will conduct current, whereas when the potential applied to the grid of tube 710 is less than the bias indicated by line 1219, tube 710 will conduct substantially no current.

As indicated in Fig. 12, during the first interval of time of the step voltage illustrated by the segment of 1230 of curve 1218 the potential applied to the tube of grid 710 is greater than the bias potential indicated by line 1219. Consequently, tube 710 will amplify and conduct the current. The output of tube 710 is coupled to tube 711 and this in turn, through tubes 712 and 714. Each of these tubes operates as a limiting amplifier and causes a square wave form in the output of tube 714. In other words, the output of tube 714 is some fixed positive value when the potential applied to the grid of tube 710 exceeds the bias represented by line 1219 in Fig. 12.

Thus, under the conditions assumed during the first pulse interval with segment 1230 above line 1219 a predetermined high positive potential appears in the output circuit of tube 714 which is connected by means of conductor 724 to screen of tube 715.

Under these circumstances when the positive timing potential 1108 is applied to the grid of tube 715 a pulse of current will be transmitted by tube 715. The timing potentials are applied to the grid of tube 715 in a manner described in connection with the discussion of the timing circuit. The positive ones of these timing pulses will cause a pulse of current to be transmitted through tube 715 when the screen has a high positive value but substantially no pulse will be transmitted through this tube when the potential applied to the screen of this tube is of a low value.

The output of tube 715 is coupled to tube 716 which is in turn coupled through the succeeding tubes 717 and 718 to an output in tube 719. Tubes 715, 716, 717 and 718 operates as overload amplifier tubes and thus tend to both limit the pulse and to shape it. Of course each of the tubes turns the pulse over so that when a positive pulse is applied to the grid and screen of tube 715, a positive pulse will similarly be applied to the grid of the power tube 719.

Tube 719 operates as a so-called cathode follower tube and repeats the positive pulse to tube 620. Tube 620 operates as two cathode follower tubes, one of which repeats the positive pulse to tube 417 and the other to tube 611.

As pointed out above, the timing pulses 1108 which are applied to the grid of tubes 715 are of a short duration. Furthermore, it requires a short interval of time for the transmission of a pulse through the amplifier and limiter comprising tubes 715 and 719 inclusive so that by the time a pulse is applied to the grid of tube 417 from tube 620, the pulse as applied to the grid of tube 715 has been terminated. It will be obvious to persons skilled in the art that if the delay or transmission through tubes 715, 716, 717, 718 and 719 is insufficient an additional delay network may be inserted between the output of tube 719 and the input of tube 620, or between the output of the right hand section of tube 620 and the grid of tube 417, or such a delay network may be employed at both places. Consequently, the operation of tube 417 and the succeeding tubes as will now be described does not in any way alter or interfere with the pulse transmitted through the amplifier comprising tubes 714 and 719 inclusive.

As described above, the step wave form generated by the step wave generator shown in Fig. 3 is applied through coupling condenser 418 to the screen of tube 417. The time constants of the coupling condenser 418 and resistance 439 are such that the potential of the screen of tube 417 accurately follows the step wave form. In other words, the voltage curve applied to the screen of tube 417 is a step wave form of the form shown in curve 1115, which is derived from the wave form of the charge on condenser 330 as described above. When the first pulse transmitted through the amplifier comprising tubes 715 through 719 as described above is applied to the grid of tube 417, the potential upon the screen of this tube will be at its maximum value illustrated by the first or top step of curve 1115.

As shown in Fig. 4, tube 417 is a pentode type tube. Tubes of this type are known to act as constant current tubes, sources or generators and pass a constant current independent of the plate voltage but dependent upon the combined screen and grid voltages applied to the tube. Consequently, during the time the transmitted pulse is applied to the grid of this tube, a constant current will flow through its anode circuit, the value of which depends upon the value or magnitude of the screen voltage. The total quantity of charge passing through the tube during the short interval of time that this transmitting pulse is applied to the grid will consequently likewise be a function of the voltage applied to the screen of this tube. The magnitude of the transmitted pulse and the screen voltage applied to the screen of the tube is such that the quantity of charge passing through the tube 417 during the first transmitted pulse described above represents a charge which will alter the potential on the sampling condenser 413 by an amount equal to half the potential representing the maximum signal magnitude which can be transmitted over the system. Consequently, during the application of these two voltages to the screen and grid of tube 417, the sampling condenser 413 will be discharged so that its potential will decrease half the total of the maximum possible change of value that this condenser can acquire. This change is illustrated in curve 1217 which falls to the value represented by the line 1236 at this time.

The circuits thereafter remain in this condition until the second of the negative timing pulses 1109 is transmitted from the code element timing circuit. At this time the step voltage upon the condenser 330 is increased as described above. Consequently, the anode voltage of tube 424 is likewise increased so that the total current through the common anode resistance 430 assumes a value which produces a voltage on its upper terminal represented by the segment 1231 of curve or broken line 1218. It is noted that the line 1231 which represents the voltage applied to the grid of tube 710 is less than the bias voltage of this tube represented by line 1219. Consequently, only a very small voltage is applied to the screen of tube 715. As a result, when the next positive code element timing pulse 1108 is applied to the grid of tube 715, no pulse will be transmitted through the amplifier comprising tubes 715 and 719 inclusive. Consequently the charge on condenser 413 will not be altered at this time. At a later time the third negative timing pulse will cause the step voltage of condenser 330 to be again increased which in turn causes the anode voltage of tube 424 to be again increased to its third step or value. At this time the total voltage across resistance 430 due to the current flowing through tubes 423 and 424 will be increased to a value represented by the segment 1232 of the curve 1218. This segment represents a voltage which is in excess of the bias voltage applied to tube 710. Consequently, when the third positive timing pulse is applied to grid of tube 715, a large positive screen voltage will also be applied to this tube so that a signaling pulse will be transmitted through the amplifier comprising tubes 715 through 719. This voltage is again fed back to the grid of tube 417. At this time the screen potential applied to the tube 417 will be the value represented by the third step of the step wave form. Consequently, a smaller current passes through the tube 417 at this time and reduces the charge on condenser 413 by a smaller amount. The charge on the condenser 413 is reduced to a value represented by the segment 1237 in Fig. 12. Thereafter, the above cycles of operation are repeated until the charge on the condenser 413 has been reduced to its lowest value and the corresponding pulses transmitted through the amplifier. In the specific example assumed herein, the first, third, fifth and sixth pulses are each transmitted as a short current pulse whereas no current is transmitted during the time the second and fourth pulse normally would be transmitted. This code combination of pulses is representative of the amplitudes of the complex wave form 1101 at the instant of time represented by the dot 1103.

Thus in forming a code group of pulses representing the magnitude of a sample and accordingly the amplitude of a signaling wave at a given instant of time, a stopped wave is generated for comparison with the sample. The magnitude of the first step of this wave is, in the exemplary embodiment of the invention described herein in detail, substantially equal to one-half of the maximum possible amplitude of the sample as employed in the comparing apparatus and circuits. Each succeeding step of the comparing wave is then one-half of the immediately preceding step. If the first step of the step wave exceeds the sample, no pulse is formed or transmitted during this step. If the sample exceeds the first step of the step wave, a pulse is formed during the first step. Incident to the forming of this pulse the sample is reduced or neutralized by one-half of its maximum possible value, i. e., the same ratio of the maximum possible magnitude as the step of the step wave form. This pulse then represents one-half of the possible maximum amplitude and when present means that the amplitude of the sample exceeds one-half of its maximum value.

The sample or the residue of the sample is then compared with the next step which is one-half of the first step or one-quarter of the maximum range of the sample and a pulse transmitted or not, depending upon the relative magnitudes of these quantities. If a pulse is transmitted the sample is reduced or neutralized by one quarter its maximum possible value and the process repeated until the pulses of a group have been formed; i. e., the character of all the pulses of a group determined, and then the process is repeated for the next sample.

In the exemplary embodiment described in detail here, the first step of the step wave form is substantially one-half the maximum input signal in the comparison circuit; the first pulse, if transmitted, represents one-half of the maximum amplitude of the input signal; and incident to the formation of this pulse the sample is reduced by one-half the maximum possible value and for each succeeding step or pulse, all the values are reduced to one-half the value they had on the immediately preceding step or pulse. Persons skilled in the art will readily understand that the system will work when these values are other suitable fractions, less than one. They may all be the same fraction or they may be all different fractions, and they need not be the same fraction for each step or pulse.

The transmitted pulses are represented by currents and shown by the lines 1221, 1223, 1225 and 1226 shown in Fig. 12. The dotted lines 1222 and 1224 represent the positions of the two pulses which are not transmitted. As will be readily apparent to persons skilled in the art, the various combinations or permutations of pulses which may be transmitted will each represent a different amplitude of the complex wave. Similarly, the number of pulses determines the number of different amplitudes which may be represented by the different combinations of the pulses. With six pulses as employed in the exemplary system described herein, it is possible to represent and transmit 64 separate and distinct amplitudes. If only five pulses are employed, it is possible to transmit and represent only 32 separate and distinct amplitudes, whereas if seven pulses are employed it is possible to represent 128 different amplitudes. In other words, the number of different amplitudes which may be transmitted by a given number of pulses where the pulses consist of two different values of current such as current or no current may be represented by 2^n where n is the number of pulses transmitted. The pulses transmitted and the manner of forming them into groups or combinations of a fixed number is sometimes referred to as a permutation code group of pulses. At other times such pulses are said to represent binary numbers, that is, numbers with a base of two, instead of the base ten as in the decimal system, in which each place, rank, or order of the number can have only two digits instead of ten, as in the decimal system. If a series of pulses is considered to be or to represent a binary number then each pulse position is an order, rank or place of the number and the pulses are the digits, and for example no current in a pulse position usually represents a zero and current represents a 1. In this way each pulse group may be said to represent a binary number, the binary numbers in turn representing the respective instantaneous amplitudes of the complex wave form.

The input of tube 720 is connected to the cathode of tube 719. Consequently, the pulse transmitted through the amplifier comprising tubes 715 through 719 is repeated by tube 720 and transmitted over the transmission path 780 to a distant receiving station shown in Figs. 8, 9 and 10. As indicated hereinbefore, the transmission path 780 may include radio transmission paths, wave guide transmission paths, a coaxial line, cable conductors, an open way line or submarine cable which is capable of transmitting the necessary frequency range. For the purpose of illustration this transmission path is shown in the drawing to comprise a coaxial line 780. It will be readily appreciated by persons skilled in the art, however, that any of the other types of transmission paths may be employed or combinations thereof when they are supplied with their proper terminal apparatus as well as suitable repeaters.

Decoding the received pulse groups

The pulses are transmitted over transmission path 780 to a receiving station where they are decoded and the complex wave form reconstructed, the receiving station provided with a synchronizing oscillator 810 which is normally controlled by synchronizing current or pulses received over the transmission path 580. If the transmission path 580 becomes ineffective or inoperative, then the oscillator 810 may control the receiving station as described hereinafter. The current received over line 580 or from the oscillator 810 is employed to control the pulse generator circuit comprising tubes 811, 814, 815, 816 and 817, inclusive. Tubes 811 through 817, inclusive operate in substantially the same manner as described above with reference to tubes 511, 514, 515, 516 and 517 and cause a series of positive synchronizing pulses to be generated and also a series of negative synchronizing pulses interspersed between the positive pulses. The negative synchronizing pulses are delayed by means of delay network 822 which operates similarly to delay network 522.

The positive synchronizing pulses are represented by lines 1305 in Fig. 13 while the delayed negative synchronizing pulses are represented by lines 1304.

The delay negative synchronizing pulses are amplified by tube 910 and applied to tubes 911, 919, 920 and 921, inclusive which tubes generate the code element timing pulse such as shown by the broken line 1307 in Fig. 13. The operation of tubes 911, 919, 920 and 921 is substantially the same as the operation of tubes 311, 319, 320 and 321 as described above in generating the pulse represented by line 1107 in Fig. 11. It will be noted, however, that the first amplifier tube 910 is a pentode tube in place of a twin triode with both sections operated in parallel. So long as sufficient output is obtained from either type of tube, they may be interchanged, the function of the tubes being merely to secure the desired output wave form and to supply the required amount of power.

Tubes 930, 935 and 940 are employed to generate a step wave form. The operation of these tubes, however, is not the same as the operation of tubes 323, 327, 329 and 331 which generate the step wave form at the transmitting station. However, the wave form generated by these tubes is substantially the same as the wave form generator at the transmitting station as described above. Consequently either arrangement may be used at either station.

The output of tube 910 which changes the delayed negative synchronizing pulse into a positive pulse is applied to the grid of the left-hand section of tube 930. The left-hand section of tube 930 is normally biased so that the grid thereof is maintained negative with respect to the cathode at all times except when the positive synchronizing pulse from tube 910 is applied thereto. When this synchronizing pulse is applied, the grid of the left-hand section of tube 930 causes the the tube to conduct current and charge the condenser 931 to a high positive value. At the end of the synchronizing pulse the grid of the left-hand section of tube 930 again becomes negative, thus cutting off the tube and preventing a further control of the potential and charge upon condenser 931 by the left-hand section of tube 930. A resistance 943 is connected in parallel with condenser 931 and serves to discharge it. As pointed out above with respect to condenser 325 and resistance 324, the potential upon the upper terminal of condenser 931 decays or is reduced in accordance with the exponential curve or law as is well known to persons skilled in the art. Curve 1313 in Fig. 13 shows the manner in which the voltage on the upper terminal in condenser 913 varies in time after the termination of the synchronizing pulse. The upper terminal in condenser 931 is coupled through the condenser 933 to the screen of the pentode tube 935. The time constant of the coupling network comprising condenser 933 and resistance 934 is such that the potential of the screen of tube 935 is accurately controlled and maintained at all times at a voltage the wave form of which is substantially the same as the wave form of the voltage upon the upper terminal of condenser 931.

The synchronizing pulse from tube 910 is also applied to the grid of the right-hand section of tube 930. This grid is likewise normally maintained negative except during the time the synchronizing pulse is applied thereto. When the synchronizing pulse is applied to the grid of the right-hand section of tube 930 it will cause the tube to conduct an appreciable quantity of current and thus charge condenser 932 to a positive potential. Thereafter, the grid is returned to its lower or negative value or potential, whereupon the right-hand section of tube 930 has no further effect upon the potential of the upper terminal of condenser 932 until a succeeding synchronizing pulse is applied to this grid.

The upper terminal of condenser 932 is connected to the grids of both sections of tube 940, which sections due to their cathode resistances 941 and 942 operate as cathode follower tubes and repeat the voltage of the upper terminal of condenser 932 to output or utilization circuits without in any way materially altering or effecting the charge or voltage of the upper terminal of condenser 932.

The grid of tube 935 is shown coupled to the output of the code element timing circuit through a small condenser 944. This condenser and resistance 945 have a very short time constant so that they will in effect differentiate the output wave from tube 921 and cause positive and negative timing pulses to be applied to the grid of tube 935. Inasmuch as the grid of this tube is normally maintained negative, the negative timing pulses will produce no effect upon the tube or currents flowing through it. However, when the positive pulses are applied to this grid it will cause the tube to conduct. The operation of tube 935 at these times is similar to the operation of tube 417 described above. In other words, each of the positive pulses applied to the grid will cause the flow through the anode cathode circuit of a current which is a function of the screen voltage applied to the tube. In other words, the total quantity of current passing through the tube is a function of the screen voltage at the time the timing pulse is applied to its grid. The time and magnitude of the timing voltage remains substantially constant. Consequently, the total quantity of current passing through the tube each time a timing pulse is applied to this grid depends upon the value of the screen voltage at that time. The anode of tube 935 is connected to the upper terminal of condenser 932 so that the current drawn by the tube during each of the timing pulses is supplied to the condenser 932 which is partly discharged thereby. At the time the first positive timing pulse is applied to the grid in tube 935, its screen will have a value represented by point 1315 on curve 1313. Consequently, the total quantity of charge removed from condenser 932 will be such that its voltage will be reduced by half of its previous value. This voltage changes during the very short interval during which the timing pulse is applied to the grid of tube 935. Thereafter, the potential of condenser 932 remains substantially constant until the next positive timing pulse is applied to the grid of this tube at which time the voltage upon condenser 932 is again reduced to half of the remaining value. In this manner the voltage upon the upper terminal of condenser 932 is reduced each time by an amount equal to half the voltage remaining on the condenser. Thus, the wave form of the voltage of the condenser 932 and also the voltage output from the cathode follower sections of tube 940 are shown by a broken line 1314 in Fig. 13. It will be noted that this wave form is substantially the same shape as the output wave form 1115 from the cathode follower tube 331.

The code pulses received over channel 780 from the distant transmitting station first pass through the delay or phasing network 1030 which is any type which will pass the code pulses and at the same time delay them so that they will be in proper phase relative to the synchronizing voltage transmitted over the transmission path 580. The pulse output from the delay or synchronizing network 1030 is applied to the input circuit of tube 1018 which repeats these pulses and applies them to the input circuit of tube 1011.

Tubes 1010, 1011 and 1012 serve to decode the received pulses and generate a pulse of varying magnitude, the magnitude of which is represented by the code group of pulses received over channel 780.

The left-hand section of tube 1010 is biased to cut off so that normally the anode cathode circuit of this section of tube 1010 does not in any way control or effect the potential of condenser 1014 connected in the cathode circuit thereof. However, when a positive synchronizing pulse is applied to this grid from the output of tube 910 it causes a current to flow in the anode-cathode path of the left-hand section of tube 1010 and charge the condenser 1014 to a positive value. The upper terminal of condenser 1014 is connected to the grid of the right-hand section of tube 1010 which acts as a cathode follower stage and repeats this voltage without materially altering or affecting its value or wave form to the screen of tube 1012. The upper terminal of condenser 1014 is also connected to the anode of tube 1011. The screen of tube 1011 is connected through the condenser 1024 to the output of the step wave generator circuit. The time constant of the coupling condenser 1024 and resistance 1025 is such that the wave form of the voltage of the screen of tube 1011 is substantially the same as the step wave form generated by the step wave generator. Tube 1011 operates in a manner similar to the manner in which tubes 935 and 417 operate. Namely, it causes a predetermined quantity of current to pass through it during the application of each of the signaling pulses to the tube. This predetermined quantity varies between the various pulses applied to the grid in accordance with the value of the voltage applied to the screen, and inasmuch as the voltage of the screen at the times the various pulses are applied is at successive decreasing values the amount of charge passing through the tube will likewise successively decrease for each of the pulses applied to the tube. Consider now the operation of this circuit under the specific conditions assumed above in which Nos. 1, 3, 5 and 6 signaling pulses are present and Nos. 2 and 4 are absent. When the No. 1 pulse is received and applied to the grid of tube 1011, its screen will be at its maximum step voltage. Consequently, half of the charge will be removed from the condenser 1014. When the screen of the tube 1011 is at its second step value no pulse is received or applied to the grid of tube 1011. Consequently, the potential of condenser 1014 is not altered at this time. When the screen of tube 1011 is at a value determined by the third step of the step wave form applied thereto, the received pulse will cause a smaller amount of charge to be removed from condenser 1014. The time and amount in which the charge is removed from condenser 1014 is shown by curve 1407 of Fig. 14. Thus, when the first pulse is received which is illustrated by line 1401, the condenser is discharged as shown in curve 1407. Inasmuch as no second pulse is received which would be at the position indicated by the dotted line 1402 in Fig. 14, the potential of condenser 1014 remains constant at this time. When the third pulse represented by line 1403 in Fig. 14 is received, the potential of condenser 1014 is further reduced. The action of the circuits as described above is repeated for each of the succeeding pulses. If the pulses are received the charge on the condenser 1014 is reduced by a smaller and smaller amount. If no pulses are received the charge on the condenser remains substantially constant.

As a result, the amount of charge removed from the condenser is equivalent to the magnitude represented by the code group of pulses received over channel 780, which code group of pulses represents the amplitude of an applied complex wave at a particular instant of time.

The voltage of the upper terminal of condenser 1014 is repeated through the right-hand section of tube 1010 to the screen of tube 1012. The grid of tube 1012 is coupled to the positive synchronizing or control pulse from the control pulse generator shown in Fig. 8. Consequently, after all of the signaling pulses have been received and employed to control the potential of the upper terminal condenser 1014, the positive synchronizing pulse is applied to the grid of tube 1012. The positive synchronizing pulse causes tube 1012 to pass a pulse of current, the magnitude of which is dependent upon the value of the screen potential applied to the tube at that time. This pulse is transmitted through the filter 1026 which is designed to reduce or remove the 8,000-cycle component of the pulses. The pulses are then repeated through both sections of tube 1013 and applied through the filter network 1017 and terminal equipment 1015 to an output device 1016. In applying pulses of varying magnitude to the low-pass filter 1017 having in an exemplary embodiment of this invention a 4,000-cycle cut-off and any other low-pass filter equipment included in the terminal equipment 1015, the complex wave form will be reconstructed and applied to the output device 1016. As shown in the drawing this output device is illustrated by a headset. It is to be understood, however, that this device may be any sort of recording instrument such as a light valve, facsimile printer and oscilloscope, or any other type of suitable indicating device, such as a loud-speaker or other utilization circuit or device.

Curve 1417 of Fig. 14 represents the wave reconstructed at the receiving station, the heavy dots represent the points determined by the code combinations of pulses transmitted for each sample of the wave 1101 at the transmitter. Point 1418 is the point corresponding to the point 1103 for which the detailed comparison of the coding and decoding process has been traced in the preceding description. It will be noted that the form of the wave 1417 differs slightly from that of the wave 1101 which is due to the quantizing effect of the system, i. e. the amplitude is represented by finite steps rather than by continuously variable function.

Monitoring equipment

While it is not essential to the operation of the system to provide monitoring equipment at the various stations, such equipment is very helpful in properly adjusting and maintaining various portions of the system in proper operating adjustment. Monitoring equipment may be similar to or a duplicate of the receiving equipment described above. Such equipment is disclosed in Fig. 6 for monitoring the signals as transmitted to enable the attendant at the transmitting point to readily determine the operation of the system and maintain it in proper adjustment. Inasmuch as this equipment operates in substantially the same manner as the receiving equipment described at the receiving station, this description will not be repeated.

While similar equipment may also be employed for monitoring purposes at the receiving station, a different form of monitoring circuit is shown in Fig. 10 and comprises tubes 1019 and 1020 and associated equipment.

As described above, the received signals after passing through the phasing network 1030 are repeated by amplifier tube 1018. These are applied to the grid of the pentode tube 1019 which acts like a current amplifier, source, or generator. The screen of tube 1019 is connected through a suitable coupling condenser to the step wave generator. Consequently, the current pulses from tube 1019 will be of an amplitude determined by the screen voltage at the time these pulses are received. Inasmuch as the screen voltage decreases by successively smaller amounts, each of these current pulses will be successively smaller in magnitude. The received pulses as amplified by tube 1019 are illustrated in Fig. 14 by the lines 1411 through 1416. Under the assumed set of conditions, the first pulse will be present and repeated by tube 1019. As repeated by tube 1019 this pulse will have a magnitude illustrated by line 1411 in Fig. 14. The second pulse is absent so nothing can be repeated by tube 1019. However, if this pulse had been present, it would have had a magnitude in the output of tube 1019 represented by the dotted line 1412 in Fig. 14. The third pulse is present so it is repeated by tube 1019 with a magnitude illustrated by line 1413 in Fig. 14. No fourth pulse is received so that there is no output from tube 1019 at the time indicated by the dot line 1414. The succeeding pulses being present are repeated with magnitudes illustrated by the succeeding lines 1415 and 1416. These pulses are applied to the filter equipment 1021 and terminal equipment 1022. It should be noted that this filter is terminated in a condenser. Such a termination of a low-pass filter is sometimes called a shunt termination. When these pulses are applied to a low-pass filter such as 1021 or other low-pass filter equipment included in terminal equipment 1022, they cause the complex wave form to be regenerated in substantially the same form as applied to the transmitting station with only minor errors or distortions therein.

The main receiving equipment may also be of the type shown as monitor equipment at the receiving station as will be readily apparent to persons skilled in the art. Likewise, the monitor equipment at the transmitting station may also be similar to the monitor equipment at the receiving station instead of the monitor equipment shown in the drawing. Such modifications are at once apparent and obvious to persons skilled in the art.

What is claimed is:

1. Apparatus for representing an electrical quantity by means of permutation code groups of a fixed number of pulses of electricity, comprising apparatus for generating a step-wave form each step of which has a value of one-half the previous step, electronic apparatus for successively comparing said electrical quantity and said wave form during each step of said wave form, transmitting apparatus for transmitting a pulse during the first of said steps for which the magnitude of the electrical quantity exceeds the value of said step-wave form, and apparatus operative incident to the transmission of said pulse for subtracting from said electrical quantity the fraction

$$\frac{1}{2^n}$$

of the total maximum possible value of said electrical quantity, where n is the number of the step of said step-wave form from the beginning, and apparatus for thereafter comparing the remaining portion of said electrical quantity with the remaining steps of said wave form in a similar manner.

2. Apparatus for representing the magnitude

of a charge on a condenser by a series of current pulses comprising apparatus for generating a step-wave form each step of which is a fixed fraction of the previous step, electronic means for comparing the charge or voltage of said condenser with the voltage of each step of said wave form, electronic transmitting apparatus for transmitting a pulse of current during the first step of said wave form which does not exceed the voltage across said condenser, apparatus operative incident to the transmission of said pulse current for subtracting from the charge on said condenser the quantity which is equivalent to that fraction of the maximum possible charge by which the step-wave form will be reduced upon its next step.

3. Electrical apparatus for transmitting a permutatively coded series of conditions representing a sample of a signal wave in which each element of the series comprises a pulse or no pulse, which comprises a control pulse generator, means operated incident to each cycle of the control pulse generator for producing a series of code unit timing pulses and a stepped comparison wave, means operative incident to the occurrence of each timing pulse for comparing the sample with the amplitude of the stepped comparison wave at that instant and transmitting a pulse when the sample equals or exceeds the amplitude of the comparison wave at that instant, and means for reducing the amplitude of the sample by

$$\frac{1}{2^n}$$

of the possible maximum sample upon each transmission of a pulse to produce a new value for comparison with the stepped comparison wave upon the next timing pulse, where n is the ordinal number of any particular timing pulse.

4. Electrical apparatus for transmitting a permutatively coded series of conditions representing a sample of a signal wave in which each element of the series comprises a pulse or no pulse which comprises a control pulse generator, means operated incident to each cycle of the control pulse generator for producing a series of positive pulses equal in number to the number of units of the code and a corresponding series of negative pulses interspersed between said positive pulses, electronic apparatus responsive to said negative pulses for generating a step-wave form of potential each step of which is one-half the previous step and is initiated by each of said series of pulses, means operative in response to each of said positive timing pulses for comparing said sample with the amplitude of said stepped-wave form at that instant of time and transmitting a pulse when the sample exceeds the amplitude of the stepped-wave form, and electronic apparatus operative incident to the transmission of a pulse for subtracting from said quantity an amount equal to

$$\frac{1}{2^n}$$

of the maximum possible quantity, and apparatus for thereafter comparing and controlling the remainder of said quantity with the succeeding steps of said wave form in a similar manner.

5. A receiving system for converting a series of conditions each represented by a current pulse or no current, said conditions being received in succession, comprising means responsive to each pulse for producing an electrical current equal to

$$\frac{K}{2^n}$$

where K is an arbitrary constant and n represents the ordinal number of the successive conditions, and means for combining the electrical currents thus produced.

6. Apparatus for controlling the charge upon a condenser and utilizing the resulting voltage comprising a condenser, an electron discharge device having a cathode and a control element, coupling circuits for coupling said condenser in the cathode circuit of said electron discharge device, apparatus for applying a charging pulse to the control element of said electron discharge device, a second electron discharge device having an anode, cathode and a plurality of control elements, circuit connections for connecting the anode-cathode path of said second device across said condenser, apparatus for applying discharge pulses to said control elements for discharging said condenser in discrete steps and a cathode follower electron discharge tube having its input circuit also connected across said condenser and its output circuit connected to a utilization circuit.

7. Apparatus for automatically transmitting a series of signaling pulses representing the magnitude of a quantity whose range of magnitudes varies between predetermined minimum and maximum values, which comprises wave generating equipment for generating a stepped-wave form each step of which is a predetermined and different fraction of said range, comparing equipment for comparing said quantity and said wave form, pulse transmission apparatus for transmitting a pulse when said quantity exceeds a step of said wave form, and control apparatus for reducing the effect of said quantity when applied to said comparing equipment by an amount equal to the fraction of said range represented by the step of said wave form when said pulse is transmitted.

8. Apparatus for representing the magnitude of an electrical quantity by means of a series of sequential pulses in which each succeeding pulse represents a successively smaller portion of the total possible amplitude of said quantity which comprises means for producing a standard of comparison of decreasing magnitude, means for comparing said quantity at successive intervals with said standard of comparison of decreasing magnitude, and apparatus for forming a pulse when the magnitude of said quantity exceeds the magnitude of said standard.

9. Apparatus for representing the magnitude of an electrical quantity by means of a series of sequential pulses in which each succeeding pulse represents a successively smaller portion of the total possible amplitude of said quantity which comprises comparing means for comparing said quantity at successive intervals with a standard of comparison of decreasing magnitude, apparatus for forming a pulse when the magnitude of said sample exceeds the magnitude of said standard, and electronic apparatus operative incident to the forming of a pulse for subtracting from said quantity an amount equal to the fraction of the total magnitude represented by said pulse.

10. Apparatus for reconstructing a complex wave from a series of groups of permutatively coded signaling pulses each representing a succession of instantaneous amplitudes of the complex wave form in which each pulse of a group

represents a different fraction of the total possible instantaneous amplitude of said complex wave form which comprises electronic apparatus for generating a current pulse in response to the reception of each of said pulses, means for varying the amplitude of each of the pulses of each of said groups in accordance with the fraction of the total instantaneous amplitude of said wave represented by each pulse of said groups of pulses, a low-pass electric filter and connections for transmitting said current pulses of varying amplitude to said filter.

11. In a communication system, a synchronizing pulse generator comprising a multivibrator, a pulse clipping amplifier, a coupling network connected between said multivibrator and said amplifier, and equipment for varying the time constant of said coupling network to vary the width of said pulse independently of the rate of recurrence of said pulse.

12. A communication system comprising a station, impulse signaling paths terminating at said station, impulse transmitting apparatus associated with certain of said paths, impulse receiving apparatus associated with others of said paths, common equipment associated with both said transmitting and receiving apparatus comprising a control pulse generator, a timing circuit controlled by pulses from said generator and a step-wave generator, a source of complex waves to be transmitted and apparatus for comparing the step-wave from said step-wave generator with said complex waves and generating a series of pulses under control of said comparing apparatus, and connections for controlling said receiving apparatus by a series of received pulses and by said step-wave generator for synthesizing the complex wave represented by said pulses.

13. In a communication system, apparatus for sampling a signaling wave at recurring intervals of time, apparatus for generating for each sample a series of pulses in which each of the succeeding pulses of each series always represents a fixed and smaller fraction of the maximum possible amplitude of said sample, decoding apparatus for varying the magnitude of the respective pulses of each of said series in accordance with the fraction of the total maximum signaling wave represented by each of said pulses, and apparatus for regenerating said signaling wave from said pulses of varying magnitude.

14. In a communication system, apparatus for measuring the instantaneous amplitude of a complex wave at predetermined instants of time comprising a step-wave generator each step of which is a different fraction of the total possible amplitude of said complex wave, a comparing circuit for comparing said amplitude with the output of said step-wave generator and other apparatus operative incident to the operation of said comparing circuit for transmitting a series of pulses representative of the magnitude of said complex wave at each of said instants of time.

15. In a communication system employing apparatus for transmitting a plurality of series of pulses each series representative of an instantaneous amplitude of a complex wave form, a step-wave generator for producing a step-wave form for comparison with each of said instantaneous amplitudes of said complex wave form, comprising an electrical condenser, apparatus initiated incident to each of said series of pulses for discharging the condenser, and means for supplying to the said condenser at recurring intervals of time successively decreasing quantities of electrical charge.

16. In a communication system employing apparatus for transmitting a plurality of series of pulses each series representative of an instantaneous amplitude of a complex wave form, a step-wave generator for producing a step-wave form for comparison with each of said instantaneous amplitudes of said complex wave form, comprising a condenser, apparatus initiated incident to each of said series of pulses for charging said condenser, and means operative at successive instants of time between successive chargings of said condenser for removing successively smaller quantities of charge from said condenser.

17. In a pulse code transmitter an oscillating circuit for timing the pulses to be transmitted comprising an electron discharge device having an anode, a cathode and a control element, an oscillating circuit comprising a condenser and an inductance connected to the cathode of said electron discharge device, bias potentials connected to said electron discharge device for normally maintaining the anode-cathode path of said device non-conducting, other apparatus for applying a synchronizing pulse to the control element of said device in timed relationship with the oscillations of said oscillating circuit for controlling the phase of the oscillations of said oscillating circuit, a second electron discharge device connected for cathode follower operation, connections for connecting the input circuit of said second electron discharge device to said oscillating circuit and other connections for connecting its cathode to a utilization circuit.

18. In a transmission system, apparatus for automatically transmitting a series of pulses representing the amplitude of a complex wave at a predetermined instant of time which comprises producing an electrical quantity proportional to the amplitude of said wave, wave generating equipment for generating a step wave form comprising apparatus for generating an exponential wave form and apparatus for controlling the values of said steps by said exponential wave form, comparing equipment for comparing said quantity and successive steps of said step wave form, pulse transmitting apparatus for transmitting pulses under control of said comparison equipment, and other apparatus for reducing the effect of said quantity as applied to said comparing equipment incident to the operation of said comparing equipment.

19. A communication system comprising a source of complex waves, apparatus for sampling the magnitude of said complex waves at recurring instants of time, apparatus for generating a comparison wave form for each of said samples having a magnitude at successive instants of time which are exponentially related, comparing apparatus for comparing said comparison wave form with said sample at said successive instants of time, and pulse transmission apparatus for transmitting pulses under control of said comparison apparatus.

20. In a communication system, apparatus responsive to permutation code groups of pulses comprising apparatus for producing an electrical wave form for each of said code groups of pulses which wave form has magnitudes which are exponentially related at times assigned to successive pulses, and apparatus responsive to receive pulses of each code group for momentarily applying said current to a summing device.

21. In a communication system, apparatus responsive to permutation code groups of pulses

comprising apparatus for producing a current wave form for each of said code groups of pulses having magnitudes which are exponentially related at times assigned to the successive pulses of each code group, apparatus responsive to receive pulses of each of said code groups for momentarily applying said current to a summing device and apparatus responsive to said summing device for constructing a complex wave form.

22. In a communication system, apparatus responsive to permutation code groups of pulses comprising means for producing an electrical wave form individual to each received code group of pulses for changing the magnitude of said pulses, electronic means for combining said wave form with the corresponding code group of received pulses and circuit utilizing means for utilizing said pulses when combined with said electrical wave form.

23. Apparatus for reconstructing a complex wave from a plurality of groups of permutatively coded signaling pulses, each group of which represents the instantaneous amplitude of the complex wave form at a given instant of time in which each pulse in each group represents a different fraction of the total possible amplitude of said complex wave form, apparatus for generating a decoding wave form having a magnitude at times assigned the respective pulses which is a function of the fraction of the total possible amplitude represented by the respective pulses, and electronic means for combining said wave form and said pulses.

24. Apparatus for reconstructing a complex wave from a plurality of groups of permutatively coded signaling pulses each group of which represents the instantaneous amplitude of the complex wave form at a given instant of time in which each pulse of each group represents a different fraction of the total possible amplitude of said complex wave form, apparatus for generating a decoding wave form having a magnitude at times assigned the respective pulses which is a function of the fraction of the total possible amplitude represented by the respective pulses, electronic means for combining said wave form and said pulses, and equipment for reconstructing said complex wave form from a plurality of said groups of pulses when combined with said decoding wave form.

25. A signal transmission system comprising means for recurrently sampling the wave to be transmitted, means for producing an electrical quantity that is a function of each sample, means for producing for each sample a comparison wave having an amplitude varying with time, means for comparing said electrical quantity with said comparison wave at successive instants, means controlled by said means for comparing for establishing a signaling condition to be transmitted, and other means controlled by said means for comparing for varying said electrical quantity.

26. In a communication system means for recurrently sampling the wave to be transmitted and producing a first electrical quantity proportional to each sample, means for producing for each of said first quantities a second electrical quantity varying at an exponential rate for a predetermined period, means for comparing each of said first electrical quantities with the corresponding second electrical quantity repeatedly during said predetermined period, means responsive to each operation of the comparing means for transmitting a pulse of one characteristic when said first quantity is greater than said second quantity and of a second characteristic when said second quantity is greater than said first quantity, and means responsive to the comparing means when said first electrical quantity is greater for reducing said first electrical quantity by an amount proportional to the value of said second quantity at the time of comparison.

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