Oct. 12, 1948. J. R. PIERCE 2,451,044

COMMUNICATION SYSTEM EMPLOYING PULSE CODE MODULATION

Filed July 9, 1945 4 Sheets-Sheet 1

FIG. 1

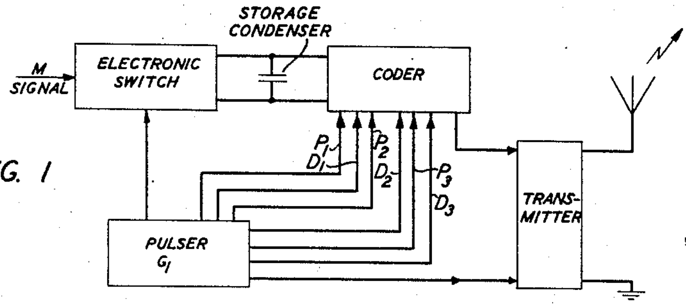


FIG. 2

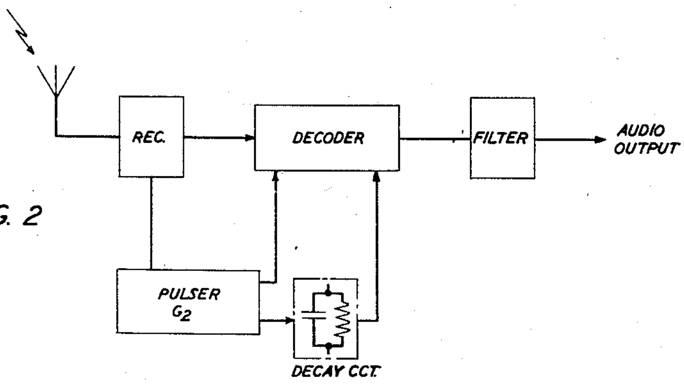


FIG. 3

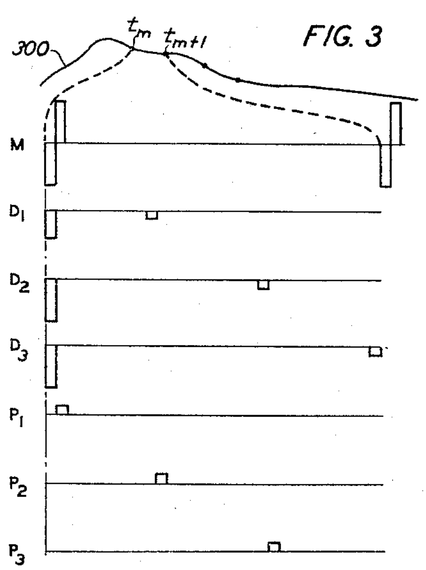
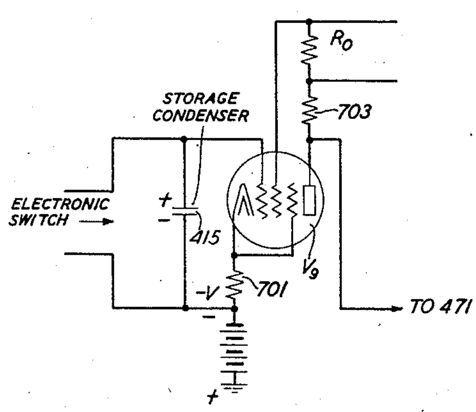


FIG. 7



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COMMUNICATION SYSTEM EMPLOYING PULSE CODE MODULATION

Filed July 9, 1945 4 Sheets-Sheet 2

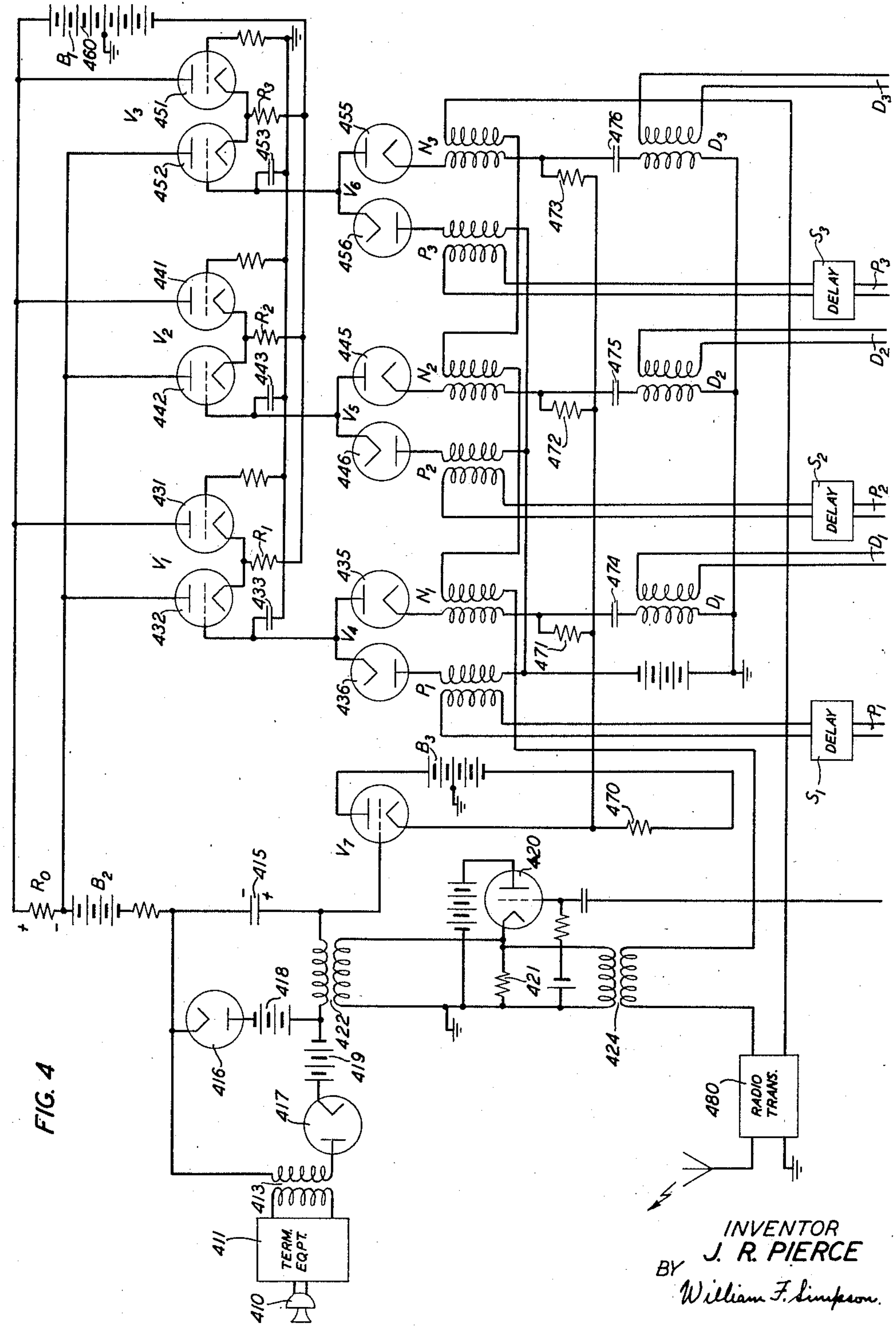

FIG. 4

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COMMUNICATION SYSTEM EMPLOYING PULSE CODE MODULATION

Filed July 9, 1945 4 Sheets-Sheet 3

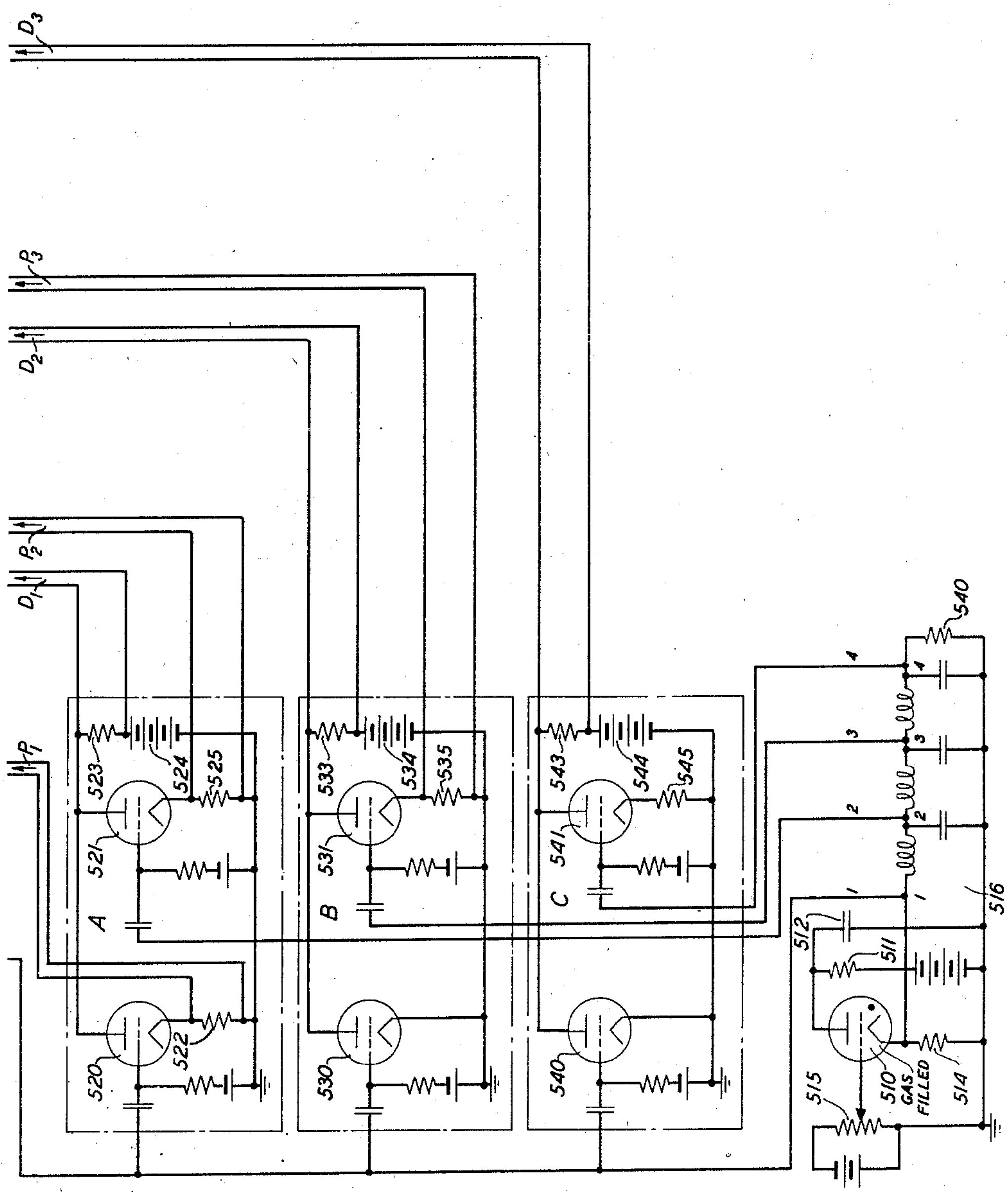

FIG. 5

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COMMUNICATION SYSTEM EMPLOYING PULSE CODE MODULATION

Filed July 9, 1945 4 Sheets-Sheet 4

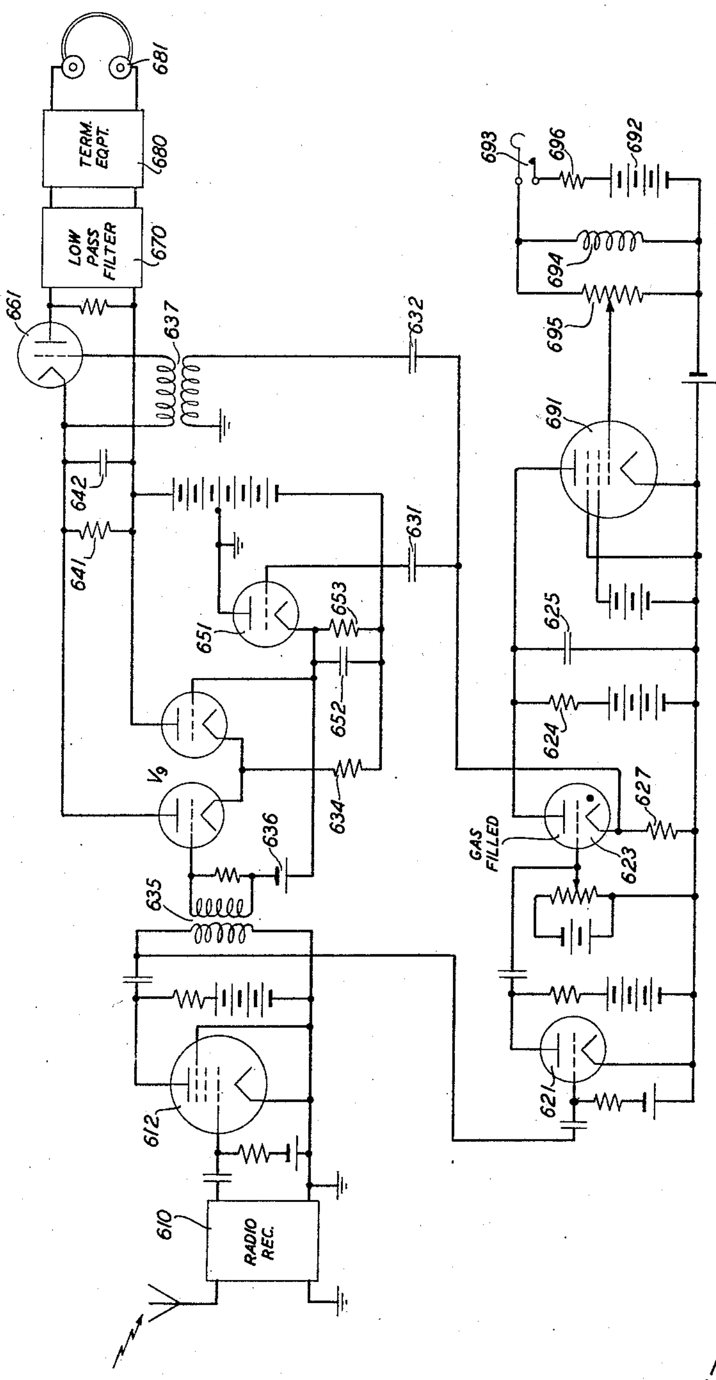

FIG. 6

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Patented Oct. 12, 1948 2,451,044

UNITED STATES PATENT OFFICE

2,451,044

COMMUNICATION SYSTEM EMPLOYING PULSE CODE MODULATION

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Application July 9, 1945, Serial No. 603,934

14 Claims. (Cl. 179—1.5)

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This invention relates to a communication system 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 pulses 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 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.

Another object of this invention is to provide improved and simplified apparatus capable of transmitting and receiving signal pulses over a channel having a low signal-to-noise ratio and deriving therefrom signals having a high signal-to-noise ratio.

More specifically, it is the object of the present invention to provide 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, all as part of a system, sometimes identified as PCM or "pulse code modulation."

Still 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 a single pulse having an amplitude which is a function of the amplitude of the original complex wave at the given instant.

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

A feature of the invention is that of accomplishing the above objects with a small number of pulses requiring a minimum of apparatus and equipment, taking advantage of the considerable distortion permissible in speech without loss of intelligibility. The invention is similar in some respects to my copending applications, Case 28 and Case 29, Serial No. 592,961, filed May 10, 1945 and Serial No. 603,939, filed July 9, 1945, respectively.

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.

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

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

The electrical quantity takes on the character of a voltage drop over an impedance which drop is increased step by step and is tested after each addition to see if it is below or in excess of the sample amplitude voltage. If below, then the last addition is allowed to remain and if in excess, the last addition is removed. This form of comparing the sample voltage with the drop over the impedance is then carried on step by step in smaller and smaller steps to as far a point as may be desired and in any case to an extent so that the granularity of the signal finally produced at the receiving point will be within the contemplated limits of fidelity of the system.

In the meantime there is set up and transmitted a code of pulses corresponding to the step-by-step structure of the impedance drop which thus characterizes the amplitude of the complex wave sample. In an exemplary embodiment of this invention the pulses are arranged in code groups, sometimes called permutation code groups, of pulses. These code groups are also sometimes called a binary code group of pulses. At the receiving station a control pulse generator, code element timing generator and associated apparatus are provided whereby the received pulses are employed to produce a pulse having a magnitude proportional to the magnitude of the complex wave sample at the transmission end of the system and thus the complex wave is reconstructed from a succession of such reproduced wave samples.

A special feature of the transmitter comprises a means of arriving at a binary representation of amplitude digit by digit, the largest digit being obtained and transmitted before the smaller digits are known. To achieve this, double triodes with large cathode feedback resistors are used in switching on, and perhaps off, successively several constant reference currents in such a manner that the magnitudes of the currents are little effected by the switching operation. The process of switching the current off automatically transmits the proper digit for each positional notation place. A resetting pulse may be used also for transmitter blanking and sampling. The voltage difference between the sample and a voltage drop caused by the double triodes acts through a cathode follower tube to provide a bias resulting in the selection of proper digits. The pulses for turning one double triode off and the next on succeed one another and are of opposite polarity so they may be obtained by producing two pulses of opposite sign by means of a network which produces a wave whose form is that of a derivative of the wave form of the single pulse from the pulser.

A feature of the receiver is the use of a double triode with a large cathode feedback resistor in combination with the discharge of a condenser through a resistor to change successive equal pulses, equally spaced, into pulses each having one half the amplitude of the preceding pulse. Another feature is the use of a single pulse to (1) recharge to a constant initial voltage a condenser which then gives an exponentially decaying voltage to a double triode, (2) to discharge the accumulated pulses from the double triode through an output filter.

A feature of this system as a whole is that the measurement of the sample voltage is on a linear basis, i. e. the minimum variation in the sampled wave necessary to produce a significant variation in the code representing the sample is the same magnitude for large as for small amplitudes of the sampled wave intead of being the same percentage of variation as in my application Serial No. 637,386, filed December 27, 1945, now Patent No. 2,437,707, granted March 16, 1948.

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

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

Fig. 3 illustrates the timing and nature of the pulses characteristic of the system at the transmitting end;

Figs. 4 to 6 give in detail the various circuits and operations of an exemplary system embodying the present invention, and

Fig. 7 is a modification of a portion of Fig. 4.

Referring more specifically to Fig. 1, let M be a signal function representative of any complex wave such as a speech wave, a small portion of which is indicated by curve **300** of Fig. 3. A pulse generator G_1 sets up a plurality of cycles of pulses, the cycles coming in rapid succession, perhaps about 8,000 per second. The first pulse of a cycle activates an electronic switch whereby a storage condenser is charged to a potential equal to the amplitude of the wave function at the instant of the pulse. The remaining pulses in a cycle operate in coordination with the potential on the storage condenser upon a coder as a result of which there is set up and transmitted a series of pulses of two differing signaling conditions characterizing the potential across the storage condenser and therefore the instantaneous amplitude of the wave function M.

A more detailed understanding of the transmitter end of my system will be had by reference to Figs. 4 and 5. Fig. 4 shows the sampling apparatus and the coding unit. The operation of these, however, is dependent on a pulse generator shown in Fig. 5 and since the pulser operation is independent of the circuit of Fig. 4 it will be advantageous to describe it first.

The controlling element in this portion of the system is a relaxation oscillator comprising a gas tube **510**. This relaxation oscillator is of a form well known in the art and includes a resistance **511** for charging a condenser **512**. Assuming that the condenser **512** is discharged then on closure of the circuit it is charged at a rate determined in part by the resistance **511**. When the potential of the condenser and the plate of tube **510** rises to a "firing value" the condenser suddenly discharges through the tube and resistor **514**. The duration of the discharge is short and gives rise to a sharp positive pulse across resistor **514**. The duration of this pulse and the rate at which it is followed by identical pulses can be completely controlled by the parameters of the circuit; in particular, by the values of the elements **511**, **512** and **514** taken with the potential of the grid of the tube **510** as determined by the potentiometer **515**. While several forms of relaxation oscillators may be used at this point the one shown is simple and satisfactory.

The positive pulse from **514** is now used to control the emission of pulses to various parts of the circuit. This is accomplished by connecting across the element **514** a delay circuit **516** made up of a transmission line, an artificial transmission line or a network of sections of inductance and capacitance in seriatim. The positive pulse travels down this line or network, the time of arrival at each section being spaced in accordance with the parameters of the various sections and giving rise to corresponding pulses going out over channels 1 to 4 for purposes to be described. While it is not essential that each of the pulses be uniformly spaced in time from the preceding and the succeeding pulses, the circuits and apparatus of the exemplary embodiment described in detail herein have been arranged to transmit and receive uniformly spaced pulses. The delay network is terminated by a load **540** of proper value to suppress any reflected wave.

The parameters of the relaxation oscillator may be adjusted so that pulses are delivered across resistor **514** at any frequency desired. For the purpose of my invention it is preferred to have a sampling frequency higher than that of the highest frequency component in the complex wave to be transmitted. If, for example, this wave is to be a speech wave and it is desired to transmit all components up to 3,000 cycles then it is desirable that there should be at least two samples per cycle for this highest frequency component. A suitable value, therefore, for the relaxation oscillator frequency would be 6,000 cycles although a higher value or a lower value may be used if desired.

By means of the delay circuit or "timestick" **516** one has available at the ends of the respective sections positive pulses similar to that initiated in **514** and spaced in time one after another by an interval determined by the elements in the section of the timestick. These pulses will control the operation of three units, A, B, C, in a manner now to be described.

At time t_m when the pulse is formed at **514** it is transmitted immediately to tubes **520**, **530** and **540** in the three units. The plate circuit of **520** in unit A includes the cathode resistor **522** and anode resistor **523** supplied from battery **524**. Consequently at the time t_m there will be available a positive pulse across resistor **522** and a negative pulse across **523**, to be used in the circuit of Fig. 4 as described hereinafter. A similar circuit arrangement is provided in unit B and unit C with the exception that the cathode resistor corresponding to **522** is omitted. Consequently, the negative pulse across **533** and **543** may be larger than that across **523** in a manner to be desired as pointed out later.

In the unit A there is also shown a triode **521** the output circuit of which includes resistor **525** as well as the resistor **523** with battery **524** in common with the plate circuit of tube **520**. All of the tubes **521**, **531**, **541**, as well as tubes **520**, **530**, and **540** are biased to cut off or so that only a small or substantially no current flows in their output circuits unless a positive pulse or potential is applied to their control grids. On the arrival of the pulse from **514** at the point **2** on the timestick this tube **521** is activated, yielding another negative pulse across **523** and a positive pulse across **525**. A similar circuit comprising tube **531** in unit B is activated when the pulse from **514** reaches the point **3** on the timestick and there is then available a negative pulse across **533** and a positive pulse across **535**. Similarly when the pulse over **514** reaches the point **4** it activates the circuit of tube **541** to yield a negative pulse across **543** and a positive pulse across **545**. These pulses due to the activation of tubes **521**, **531** and **541** are of substantially the same magnitude, and in general are less than the initial pulses due to activation of tubes **520**, **530** and **540**. The character of these pulses and their timing is shown in Fig. 3.

Referring now to Fig. 4, there is shown a source of a complex wave to be transmitted, such as a speech wave. This source may comprise a microphone **410** and suitable terminal equipment **411** and transmission line to supply the signal function M to the transformer **413**. Associated with the secondary of the transformer is a storage condenser **415** which tends to take on a potential difference equal to that developed in the transformer. However, since it is desired to sample the wave for brief intervals of time only, the circuit is provided with two diodes **416** and **417**. A biasing battery **419** normally prevents flow of current through diode **417** so that the condenser **417** does not charge. A positive pulse going directly from the pulse generator resistor **514** activates for a short time the tube **420** converting this into a positive-negative pulse in the secondary of transformer **422**. The transformer is so poled that the positive pulse will render diode **416** momentarily conducting in spite of biasing battery **418** and will therefore discharge the condenser **415**. Immediately thereafter the negative pulse will render diode **417** conducting whereupon the condenser **415** will be charged to a potential depending on the instantaneous amplitude of the complex wave and yielding a sample to be used as hereinafter described. On completion of the pulse the condenser **415** will hold the charge till the arrival of the next pulse on tube **320**. In parallel with the transformer **422** is the trans-

former **424**, the purpose of which will be pointed out later.

It is now the function in this system to send out a code group of a limited number of pulses characterizing the voltage across condenser **415**, that is the amplitude of the complex wave at the sampling moment. The invention will be described in terms of three pulses per group. To this end the coder previously indicated in Fig. 1 is used and the process consists, in part, of comparing the voltage over condenser **415** with that across a resistor R_0, the current therein being adjusted step-by-step until the drop over it is equal to the voltage over **415** or as near thereto as the steps defined permit.

A feature of this invention is the use of three pairs of triodes V_1, V_2, V_3, each having a cathode resistor R_1, R_2, R_3 respectively, common to its two tubes. The grid of the right-hand tube of each pair is connected to an intermediate grounded point of the B battery **460**. Normally, no current is flowing through the left-hand tube of each pair. However, making the control grid of any one of these left-hand tubes positive with respect to ground will give rise to a constant current through R_0 while making the same grid negative will turn the current off. The characteristic of a pair of triodes connected as shown is that the current flowing through its common cathode resistor tends to remain substantially constant. If a positive potential of sufficient magnitude is applied to the grid of the left-hand tube, the right-hand tube will be turned off, all the current then flowing through R_0. The cathode resistors R_1, R_2 and R_3 may be of magnitudes related to each other in any desired manner but are preferably so arranged that the current through R_0 which V_2 controls is twice that which V_3 controls, while the current which V_1 controls is twice that which V_2 controls. This is accomplished by suitable adjustments of the cathode resistors and the approximate adjustment is that in which R_2 is twice that of R_1 and R_3 is twice that of R_2.

The tubes are turned on and off by pulses applied through the pairs of diodes V_4, V_5 and V_6. The diodes of a pair are oppositely connected so that the one will pass a positive pulse and the other a negative pulse to the grid of the corresponding left-hand tubes of the pairs V_1, V_2 or V_3. Positive pulses applied through the transformers P_1, P_2 and P_3 will always turn on the respective left-hand triodes giving rise to a corresponding voltage drop across resistor R_0. These positive pulses will also charge the respective condensers **433**, **443**, **453** which will retain the charges till a negative pulse arrives. Small negative pulses applied through transformers D_1, D_2 and D_3 will turn the respective triodes off, but, as will be explained later, only if the drop across R_0 exceeds the sample potential difference on the storage condenser **415**. When a triode is turned off the current flowing through the control diode from the corresponding condenser **433**, **443** or **453** acts through transformers N_1, N_2 or N_3 to send a pulse to the transmitter **480** and this results in the transmission of a signal code pulse.

The operation of the transmitter end of the system may be understood now by combining the actions of the pulse generator with the coder. The sequence of operations is as follows: At the beginning of the cycle, determined by the generation of the positive pulse at **514**, a negative pulse is developed across resistors **523**, **533**, **543** as a result of the activation of tubes **520**, **530** and **540**. These negative pulses act through the transformers D_1, D_2 and D_3 and the corresponding diodes to turn off any of the left-hand tubes of the pairs V_1, V_2 and V_3 that may have remained conducting during the previous coding cycle. At the same time a positive pulse is developed over resistor **522** and arrives at transformer P_1, being delayed slightly by the delay network S_1. This pulse then turns on the tube **432**.

At the same time also, the positive pulse from **514** acting on the grid of triode **420** gives a positive pulse over cathode resistor **421** which in the secondary of the transformer **422** is converted into a positive-negative pulse. The positive pulse acting through diode **416** discharges condenser **415** as already described and the negative pulse thereafter, operating on diode **417**, permits the condenser **415** to be charged to a potential corresponding to the amplitude of the complex wave at that instant. The charge on the condenser **415** then remains substantially constant until the pulse of the next coding cycle arrives. The negative pulses over resistors **533** and **543**, operating through transformers D_2 and D_3, will be relatively large because of the absence of cathode resistors for tubes **530** and **540** and they will be of sufficient magnitude to overcome the biasing action of a triode V_7 and so turn off tubes **442** and **452**. The function of V_7 will be described below. As stated, the positive pulse from resistor **522**, operating through P_1, turns on tube **432** but, because of delay S_1, not until the initial negative pulses are completed. The initial pulse may also be used, if desired, to blank the transmitter through transformer **424** so that the strong negative pulses in D_2 and D_3 at this time do not result in the transmission of a signal.

The character and the timing of the pulses during one cycle are shown in Fig. 3. In this figure **300** represents a small portion of the complex wave and the dots indicate the successive sampling times. Line M is an expansion on a time basis of one cycle interval t_m to t_{m+1}, the first negative-positive pulse corresponding to the sampling at t_m and the second corresponding to the sampling at t_{m+1}. The remaining lines show the timing of pulses within a cycle in the various circuits as will appear below.

With the tube **432** turned on, tubes **442** and **452** turned off and a sample voltage stored in condenser **415**, it is desired to compare this latter voltage with the drop across resistor R_0. To this end a triode V_7 is shown with its grid connected to the one terminal of condenser **415**. With no current in R_0 and no charge on **415**, the grid of V_7 is biased back by means of battery B_2 to approximately ground potential in which case current of a definite value flows through the plate circuit of V_7. The positive potential of the upper end of cathode resistor **470** is suitably adjusted and applied through resistors **471**, **472** and **473** to the cathode of the respective diodes **435**, **445** and **455**. This provides the necessary positive bias on these cathodes so that the charge on the respective condensers **433**, **443**, **453**, does not normally leak off. Blocking condensers **474**, **475** and **476** prevent the shorting of a portion of the battery B_3 in the plate circuit of V_7 through resistance **470**.

When condenser **415** has a sample charge and a current flows through R_0, the potential of the grid of V_7 will be raised if the drop over R_0 is less than the voltage over **415**. Consequently, the

enlarged positive potential from resistor **470** will prevent negative pulses coming over transformers D_1, D_2 and D_3 from turning off the corresponding triodes **432**, **442** and **452**. If, however, the drop over R_0 is greater than the voltage over **415**, the potential of the grid of V_7 will be lowered and the positive potential from resistor **470** will be decreased. A negative pulse will then turn off the last activated double triode and, by the discharge of the corresponding condenser through a transformer N, a code signal pulse will be transmitted.

As pointed out above, after the initiation of the first pulse in the cycle, triode **432** will be turned on. Shortly thereafter, a negative pulse is applied to D_1 corresponding to the time of arrival of the pulse in the timestick **516** at the point 2, this pulse operating through triode **521** to give a negative pulse across resistor **523**. If the drop across R_0 is greater than the sample, then triode **432** is turned off and a pulse is transmitted through transformer N_1 indicating a zero in the highest order binary position. This pulse is indicated in line D_1 of Fig. 3.

When the negative pulse over **523** is set up, a positive pulse is also developed across cathode resistor **525**. This operates through a delay network S_2 to transformer P_2 which, operating through its diode, turns on triode **422**. Somewhat later tube **531** will be activated, giving rise to a negative pulse over resistor **533** which operates through transformer D_2 on tube **422**. If the drop across R_0 exceeds the sample on the condenser **415**, tube **422** is turned off and a pulse is transmitted by way of transformer N_2, shown as the second pulse in line D_2 of Fig. 3. If not, V_2 remains on and no code pulse is transmitted.

With the activation of tube **531** a positive pulse is also developed across cathode resistor **535** and this operating through delay network S_3 turns on triode **452** very shortly after the testing of the effect of V_2. Still later the activation of tube **541** develops a negative pulse over resistor **543** which operates through transformer D_3 to test whether or not **452** should be turned off.

From the above description, it is seen that a combination or code of three "off" or "on" pulses will have been sent to the transmitter **480**, the code group being representative of or characterizing the amplitude of the sample as given by the potential charge of condenser **415**. This group of pulses, all rendered of the same amplitude by clipping if necessary, is accordingly transmitted to a remote receiving station.

In the exemplary system shown in the drawing the pulses are transmitted from the transmitting station to the receiving station over a radio channel. This channel, may operate in the short wave, ultra short wave or micro-wave regions where the waves have quasi-optical properties.

The signals may be equally well transmitted over open wire lines, cable conductors, a coaxial cable, wave guide, etc. or any combination of such paths including a radio path. The transmission path may also include suitable terminal equipment amplifiers, gain and phase control equipment, and other type of control and supervisory equipment.

Various ancillary elements are incorporated in Figs. 4 and 5 for reasons which will be evident to those skilled in the art. One of these is the transformer **424** the secondary of which is connected in series with the secondaries of transformers N_1, N_2 and N_3. Transformer **424** receives a pulse at the beginning of each cycle. This transformer is so poled as to block the transmitter **480** during the presence of the large negative pulses which turn off tubes **442** and **452** on the initial pulse of each cycle.

The allowable range of operation of the circuit lies between a voltage on condenser **415** which, when added algebraically to the voltage of B_2 will bring the grid of V_7 and hence the drop across **470** to certain specified values described above, and a voltage on condenser **415** which, when added algebraically to the voltage of B_2 and the drop across R_0 when the grids of tubes **432**, **442** and **452** are positive, brings the grid of V_7 and the drop across **470** to the aforementioned values. It will be apparent that by a simple phase reversal in transformer **413** either of these voltages across **415** referred to above can represent the "minimum" of the AC signal. Furthermore, leaving the circuit comprising **410**, **411**, **413**, **415**, **416**, **417**, **419** and **422** as they are, one may interchange the connections of the terminals of condenser **415** to B_2 and the grid of V_7. In this case the voltage across the condenser and that across R_0 are in the same direction and the drop across R_0 must be so adjusted by tubes V_1, V_2 and V_3 that the sum of these two voltages will be constant within the operating limits. This sum combined with a reduced B_2 voltage will then be the required voltage of the grid of V_7. The signal then transmitted represents the magnitude of the drop over R_0 as before but is now the complement of the voltage across the condenser, i. e., it is equal to a constant minus the condenser voltage. This complementary signal will carry the same information but with a 180-degree phase reversal.

Receiver

A satisfactory circuit for receiving and decoding the groups of pulses from the transmitter station is shown in Fig. 6. In this figure the message indicated as arriving on a radio carrier is detected down to pulse frequency in any suitable terminal equipment **610** and is then shown as being amplified by tube **612**. The receiver circuit itself consists essentially of a decoding portion and a pulse generating portion, the latter of which will be described first. A positive pulse arriving at the input of **612** is inverted and is transferred as a negative pulse to the grid of a tube **621** which then inverts and amplifies it, if necessary, for application on the grid of a relaxation oscillator comprising the gas tube **623**. This relaxation oscillator may be of the same general form shown in Fig. 5 and by means of the resistor **624** and condenser **625** is adjusted to substantially the same frequency as the oscillator of Fig. 5; that is, to give one oscillation for each cycle or group of pulses characterizing a sample. Furthermore its adjustment is such that it is triggered off by a positive pulse of sufficient magnitude on the grid of **623**. The positive pulse generated over cathode resistor **627** is transferred through condensers **631** and **632** to the decoder portion of the receiver circuit.

This decoder comprises the double triode V_9 wth the common cathode resistor **634**. The plate circuit of the left-hand section of V_9 includes the condenser **642**. A resistor **641** may be included, but not necessarily, in parallel with condenser **642**. The bias of that section is such that it is at or below cut-off. If, however, its grid receives a positive potential its current will rise at the expense of the current in the right-hand section. If an "on" pulse arrives from the transmitting station, the relaxation oscillator is triggered, a positive pulse of short duration is impressed on the grid of tube **651** and a charge is stored on condenser **652** which condenser then discharges exponentially through cathode resistor **653**. The potential of the condenser **652** is impressed on the grids of both sections of V_9 and it will be observed that this is always a positive potential which, however, will decrease exponentially. The circuit is so arranged that the potential across the condenser **652** decreases by half its value in the time interval between successive digit pulses. If at the beginning of this cycle there is received an "on" signal then a positive pulse appears through transformer **635** on the grid of the left-hand section of V_9 and the potential of this grid is therefore equal to the potential of the pulse minus the drop through cathode resistor **634** plus the potential across condenser **652**, plus any additional bias **636**. A pulse of short duration and proportional to this grid voltage will flow through the left-hand section of tube V_9 and charge the condenser **642** correspondingly. Another pulse of a code group arriving at a later time will give rise to an additional pulse through V_9 and an addition to the charge on condenser **642**. But, although the amplitude of the arriving pulses will be the same, the potential of the condenser **652** will have decayed so that the charge received for a pulse corresponding to tube V_2 at the transmitter will be less than that for one corresponding to tube V_1 and for a pulse corresponding to tube V_3 will be still less, since the potential on condenser **652** will have decreased to a still lower value. At the conclusion of the cycle, condenser **642** will have a charge determined by the particular code group which has arrived. Then with the beginning of the next cycle a pulse will be transmitted from tube **623** through condenser **632** and transformer **637** to the grid of tube **661**, normally below cut-off. Arrival of this positive pulse, however, activates the tube and a pulse from condenser **642** will flow through the plate circuit of tube **661**, the quantity of the charge passing being equal to the charge on condenser **642** and therefore substantially proportional to the original sample.

The code groups will follow each other at a rate equal to the sampling rate at the transmitter and these may then be passed through the low-pass filter **670** into suitable terminal equipment **680** and appropriate receiver **681** (here shown as a head-set) in which there will thus be reproduced the original complex wave function.

It will be evident that the tube **623** may be triggered off by any pulse in a code group inasmuch as they all arrive with the same amplitude, and the particular place in a code cycle where the tube will be triggered off is one of chance depending on when the receiver circuits are closed. It is important, however, that its triggering shall be brought into coincidence with the first pulse in a cycle. To this end an additional feature is included with the relaxation oscillator. This may comprise a tube **691**, here shown as a pentode. Its output circuit is connected across the condenser **625**. Its input circuit comprises a battery **692** and a key **693** in series with an inductance **694**, paralleled by a potentiometer resistor **695**. There may also be included in series a current limiting resistor **696**. On closure of the key **693**, a large voltage appears across the inductance **694** which voltage, however, rapidly falls as current through **694** becomes established. The connection is such that the positive end of the inductance, operating through potentiometer 695, impresses a positive voltage on the grid of pentode 691 for a moment only. During this interval charge will be withdrawn from 625 delaying the time when the tube 623 is again ready to be triggered off. The magnitude of the pulse applied to the grid of 691 is adjusted so that the delay in triggering time is approximately one-third of the cycle period, i. e. about one digital period. By at most two or three taps of the key 693 the triggering of tube 623 may be brought into coincidence with the arrival of the first pulse in a cycle. The opening of key 693 will give rise to a large reverse voltage over inductance 694 but this has no effect inasmuch as it drives the grid of pentode 691 to a negative value.

Normally the relaxation oscillator at the receiver will be held in synchronism with the transmitter by the first digit pulse in each cycle. If the first digital signal of a cycle is an off-pulse, the relaxation oscillator will then trigger off itself and sufficiently close synchronism will be maintained, if there is not an excessive number in succession of off-signals for the first digit.

The arrangement of the diodes 416 and 417 as shown in Fig. 4 is such that the condenser 415 will always receive a negative charge on the top plate, so that the potential from this condenser plate to the grid of V_7 is positive. This, however, is not necessary. By reversal of the direction of the diodes and their biasing batteries and a reversal of transformer 422 the condenser will be charged in the reverse direction and appropriate behavior of the circuit is still obtained by a compensating change in the biasing battery B_2.

The circuit operation has also been described in terms of three digits per cycle. Obviously, a larger number may be used with corresponding increase in fidelity of reproduction. However, an objective in this invention has been to produce an operative system requiring as few and simple parts as possible.

Fig. 7 shows an alternative input to that shown in Fig. 4. In this alternative form a pentode V_8 replaces V_7 and the storage condenser is connected across the input circuit, which input circuit includes the cathode resistor 701. The plate circuit of this pentode includes the resistor R_0 and a fairly large resistor 703. The screen grid is connected to positive of battery; that is, to the positive end of R_0. Normally, current flows through the pentode of sufficient magnitude so that considering the drop through R_0 and 703 the potential of the plate is slightly positive and is directly connected to the resistors 471, 472 and 473, with the elimination of V_7 and its circuit. With no signal on the storage condenser and with the double triodes turned off the potential of the cathodes of the left-hand sections of the diodes is sufficiently positive so that the negative pulses coming up through the D transformers will not render the said diodes conducting. A signal potential on the storage condenser, lowering the potential of the control grid, will raise the potential of the plate and the corresponding diode cathodes. As the successive double triodes are turned on the increasing drop through R_0 will tend to lower the potential of the plate and they will be allowed to remain in until the lowering is so great as to overbalance the positive effect due to the voltage impressed on the control grid from the storage condenser. An advantage of this form of input is the elimination of the floating biasing battery B_2.

What is claimed is:

1. In a communication system apparatus responsive to permutation code groups of pulses of signaling conditions, a relaxation oscillator, apparatus responsive to a particular pulse of each of said code groups of pulses for accurately controlling the frequency of said relaxation oscillator, and other apparatus for shifting the control of said relaxation oscillator from one of said pulses of each code group to another of the pulses of each group.

2. In a communication system apparatus responsive to permutation code groups of pulses of signaling conditions, a relaxation oscillator, apparatus responsive to a particular pulse of each of said code groups of pulses for accurately controlling the frequency of said relaxation oscillator, and other apparatus for shifting the control of said relaxation oscillator from one of said pulses of each code group to another of the pulses of each group, decoding apparatus for decoding said permutation code groups comprising apparatus for varying the effectiveness of each of the pulses of a code group and other apparatus for adding said changed pulses of each code group together, and means controlled by said relaxation oscillator for generating a single pulse having a magnitude proportional to the sum of said added pulses.

3. In a communication system in which the amplitude of a complex wave is sampled at recurrent intervals and the sample amplitude represented by a permutation code group of pulses each of either of two different signaling conditions for transmission, means for storing a voltage proportional to the sample amplitude of the wave, means for building up a reference current of components of successively smaller amplitudes, the number of components corresponding to the number of pulses of said group, means for comparing the stored voltage with the voltage produced by the flow of the reference current through an impedance upon the addition of each component current, and means responsive to said means for comparing for establishing the signaling condition of each of said pulses.

4. A combination according to claim 3 in which the means for comparing the stored voltage with the voltage produced by the flow of reference current through an impedance comprises an electronic control device with connections for applying the two voltages in series to the input of said device, and comprising further means responsive to the output of said control device for causing the retention of that component reference current last added only if the sample voltage is in excess of said voltage produced by the flow of the reference current through an impedance.

5. In a communication system in which the amplitude of the intelligence wave to be transmitted is sampled at recurrent intervals and the sample amplitude represented by a series of permutation code pulses each of one of a plurality of different signaling conditions, means for storing a voltage proportional to the sample amplitude of the intelligence wave, a resistor, a series of constant current devices for controlling the flow of current through said resistor, means for actuating all of said devices to a first condition, means for subsequently operating said devices in succession to a second condition, means responsive to the relative values of the stored voltage and of the voltage drop across said resistor for controlling the restoration of each of said devices to said first condition prior to the actua-

tion of the next device of said series to said second condition, and means also responsive to the relative values of said voltages for controlling the signaling condition of the respective pulse of said group.

6. In a communication system in which the amplitude of an intelligence wave is sampled at recurring intervals and each sample amplitude represented by a group of permutation code pulses each of one of a plurality of different signaling conditions, means for storing a voltage proportional to the sample amplitude of intelligence waves, a resistor, a series of constant current devices for controlling the flow of current through said resistor, the number of said devices corre-ponding to the number of pulses of said group, a resistor, means for actuating all of said devices to a first condition, means for subsequently operating said devices in succession to a second condition, means responsive to the relative values of the stored voltage and of the voltage drop across said resistor for causing the restoration to said first condition of the last of said devices operated to said second condition when the voltage drop across said resistor exceeds the stored voltage and prior to the actuation of the next device of said series to said second condition and for maintaining said last operated device in said second condition when said stored voltage exceeds said voltage drop across said resistor, and means also responsive to the relative values of said voltages for controlling the signaling condition of the respective pulse of said group

7. In a communication system in which the amplitude of an intelligence wave is sampled at recurring intervals and the sample amplitude represented by a series of pulses of one of two different signaling conditions, means for storing a voltage proportional to the instantaneous amplitude of the intelligence waves, a resistor, a series of constant current generators connected to supply current to said resistor when actuated, means for actuating said generators in turn to each produce a difference voltage drop across said resistor, means for comparing the voltage drop across said resistor with the stored voltage for producing a control voltage when the stored voltage exceeds the drop across said resistor, means operating after the actuation of each generator and before the actuation of the next generator of the series for rendering inactive the generator last actuated except in the presence of said control voltage, and means responsive to said control voltage for transmitting a pulse of one of said signaling conditions.

8. In a pulse code modulation system, means for recurrently sampling the waves to be transmitted to produce a voltage proportional to the amplitude thereof at each sampling instant, a resistor, a series of sources of constant current connected to supply current to said resistor when operative, the current supplied by said sources to said resistor being so proportioned that the voltage drop across said resistor increases as the sum of the ascending powers of two as successive sources of said series are rendered operative, and timing means for: first, rendering all of said sources inoperative to supply current to said resistor; second, rendering a first source of said series operative; third, rendering said first source inoperative except when the voltage proportional to the sample is greater than the voltage drop across the resistor and transmitting a pulse of one characteristic upon the rendering of the source inoperative; and repeating said second and third steps for each source of said series.

9. In a communication system in which the amplitude of the intelligence wave is sampled at recurring intervals and the sample amplitude represented by a permutation code group of pulses of either of two different signaling conditions, means for storing a voltage proportional to the sample amplitude of the intelligence wave, a resistor, a plurality of electronic devices each connected to supply a respective constant current through said resistor when operative, means for normally maintaining each of said devices inoperative, a control capacitor associated with each of said devices and adapted when charged to maintain the corresponding device operative, a discharge circuit for each of said control capacitors, means for supplying to said discharge circuits a biasing voltage for preventing the discharge of said control capacitors except when the voltage drop across said resistor exceeds said stored voltage and a control pulse is applied thereto, and timing means for charging said control capacitors in succession.

10. In a communication system in which the amplitude of the intelligence wave is sampled at recurring intervals and the sample represented by a permutation code group of pulses of each of either of two signaling conditions, means for storing a voltage proportional to the sample amplitude, a resistor, a series of constant current devices connected to supply to said resistor component currents producing across said resistor valuation voltages that decrease in proportion to the descending powers of two as said devices are individually switched from a normal to an operated condition in succession in said series, means for switching the devices of said series from a normal to an operated condition in succession, and means operated after the switching of each device of said series from a normal to an operated condition and prior to the switching of the next device and responsive to the relative value of said sample voltage and said valuation voltage for restoring the device last switched to the normal condition or for maintaining it in the operative condition dependent on the relative value of said voltages.

11. A combination according to claim 10 in which the last-mentioned means operate to maintain the device in the operative condition when said sample voltage exceeds the valuation voltage.

12. In a communication system in which the amplitude of the intelligence wave is sampled at recurring intervals and the sample amplitude represented by a code group of pulses each of either of two different signaling conditions, means for storing a voltage proportional to said sample amplitude, a resistor, a series of constant current devices normally non-conductive and each connected to supply a component current to said resistor when conductive, a capacitor for each of said devices adapted when charged to maintain the respective device conductive, a circuit for charging each of said capacitors in response to a control pulse, a circuit for discharging each of said capacitors in response to another control pulse, means responsive to the relative voltages on said means for storing and across said resistor for rendering said circuit for discharging non-responsive to said other control pulses when the voltage on said means for storing exceeds the voltage drop across said resistor, means responsive to the operation of said circuit for discharging said capacitors for producing a signal pulse of

one condition, and timing means for producing a series of pulses comprising: first, a clearing pulse to operate all of said circuits for discharging irrespective of the relative voltages of said means for storing and across said resistor; second, a control pulse for charging the capacitor of the first constant current device of said series to render said device conductive; third, a control pulse for discharging said capacitors; and subsequently corresponding control pulses for each of the other constant current devices of said series.

13. A combination according to clair 12 in which the component currents supplied by said series of constant current devices decrease in proportion to the descending powers of two.

14. A combination according to claim 12 in which each of said constant current devices comprises a pair of electron tubes each having a cathode, an anode and a control electrode, a resistor common to the cathode circuits of said tubes, a control electrode circuit for one of said tubes for maintaining that tube normally conducting, connections from the anode of the other of said tubes for completing the circuit to said resistor in the so-called conductive condition of

the device, and connections from said capacitor for each of said devices to supply a voltage to the grid of said other device to render it conducting.

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