Transistorized Binary Pulse Regenerator

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(Manuscript received March 14, 1956)

A simple transistorized device has been constructed for amplifying and regenerating binary code signals as they are transmitted over substantial lengths of transmission line. By the use of simple circuitry, means are provided whereby the distortion in the output of one repeater due to low frequency cutoff is compensated in the next repeater. Furthermore, the repeater is effectively and simply timed from its own regenerated output. A brief discussion of the theory of the circuit is presented along with measured results and oscillograms showing its performance. The effects of extraneous interference on the production of errors in such a repeater are reported. These results are in substantial agreement with theory.

1. INTRODUCTION

Long distance communication using digital transmission is not new but was used by man in his earliest communication system. In fact, his first successful electrical system, the telegraph, made use of binary pulse codes. It was not until the invention of the telephone that the emphasis was shifted from the digital to carrier and voice systems. During recent years the development of new electronic devices and techniques have brought digital transmission into the picture again, and it now seems possible to use it not only for telephony but for television as well. Future systems will probably make use of the binary code, this choice being dictated by circuit simplicity and performance.

The fundamental requirement for perfect binary transmission is to be able to detect the presence or absence of a pulse in each of a regular set of discrete time intervals. From this requirement the principal advantages of such a system may be tabulated. First, a pulse can be recognized in the presence of large amounts of interference. Second, when a pulse is recognized it can be faithfully regenerated, suppressing the effect of the interfering noise to any desired degree. Third, simple high-efficiency non-linear devices such as multivibrators or blocking oscillators can be used to regenerate the pulses. The great disadvantage, common to all pulse systems is the large bandwidth required for transmission.

On wire lines this large transmission band will create a number of problems. The phase-loss variations, crosstalk and temperature effects will be greatly increased over the transmission band as compared to that of the more conventional systems. It can be shown however that if the repeater spans are made sufficiently short these problems will largely disappear. Only rough equalization will be needed, crosstalk and temperature effects become negligible. Furthermore the repeater power requirements will be small and the circuitry comparatively simple, since only partial regeneration will be required. The problem remains to build a regenerative repeater so simple that it will be economically sound to use on short spans of line. The development of the transistor with its small size and low power requirements has made such a repeater feasible.

1.1 *Pulse Distortion Caused by Low Frequency Cutoff*

Since the frequency spectrum of a binary pulse train will extend down to and include dc, the ideal repeater should be able to handle the complete frequency band to avoid signal distortion. This would preclude the use of coupling transformers and condensers which attenuate the low frequencies and remove the dc. Practical considerations however dictate the use of these elements which means that the repeater will have a low frequency cutoff. The distortion of a binary pulse train produced by low frequency cutoff presents one of the most vexing problems the designer of a regenerative repeater must cope with. It produces what is probably the most potent source of intersymbol interference found in an average binary pulse communication system. This interference consists of a transient response whose effect may be appreciable far beyond the end of the pulse itself.

When a train of ideal flat top pulses with infinitely steep sides is applied to a load through a condenser or a transformer, the transient response persisting beyond the end of the pulse is an exponential and may be expressed as

$$T = kP_0e^{-bt} \tag{1}$$

The time t, is measured from the end of the pulse and the damping coefficient b is a function of the low frequency cutoff.* P_0 is the amplitude

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* The value of b may be approximated by

$$b = 2\pi f_0$$

where f_0 is the frequency in cycles/sec at which the low frequency loss characteristic of the transformer is 6 db above that of the pass band.

of the pulse and k is given as

$$k = 1 - e^{-bt_p}$$

where t_p is the pulse duration. The sum of the transients of a sequence of pulses will shift the zero potential from the base of the pulse toward its average value as shown on Fig. 1(b). This phenomenon has been re-

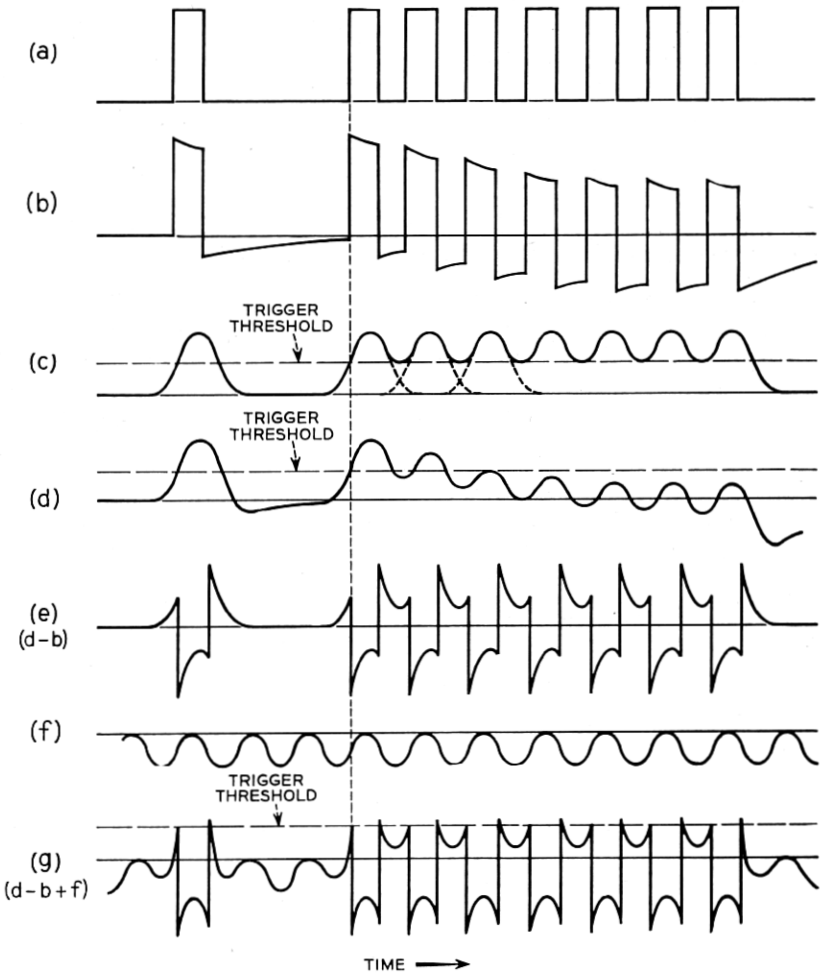

Fig. 1 — (a), a perfectly regenerated pulse train; (b) showing the effect of low-frequency cutoff; (c), showing (a) after passing over equalized line; (d), showing (b) after passing over equalized line; (e), effect of (d) minus (b); (f), inverted pedestal timing wave; (g), composite wave at input to repeater, namely, (d) minus (b) plus (f).

ferred to as "zero wander." In a regenerative repeater the trigger potential is tied to the zero level by a constant bias. Zero wander then will produce a changing bias which reduces the signal to noise margins of the repeater, or in some cases even prevents regeneration. Suppose, for example, a transmission line is equalized so the ideal pulse train shown on Fig. 1(a) will appear as Fig. 1(c) after being transmitted over the line. The individual pulses have widened until the envelope of a sequence of consecutive pulses shows as a ripple with a much smaller amplitude than the individual pulse. If the pulse train distorted by low frequency cutoff shown on Fig. 1(b) is transmitted over this line its output will appear similar to that shown on Fig. 1(d). The portion of the signal where the peak amplitude lies below the trigger threshold will not be regenerated.

1.2 *Compensation for Low-Frequency Distortion*

In the past many circuits have been devised to prevent zero wander, but none have been completely satisfactory. The repeater described in this paper effectively eliminates zero wander in a string of consecutive repeaters by means of a new and simple method. This may be better understood by referring to Fig. 2. Here are represented two successive repeaters of a transmission system. These repeaters have what appears as a conventional negative feedback loop consisting of a pair of resistors, R. The function performed by this feedback loop bears little if any resemblance to the negative feedback of linear amplifiers and is referred to as "Quantized feedback" in this paper.*

Suppose an isolated pulse of amplitude P_m is regenerated in repeater M and is applied to the line through its output transformer. The low frequency cutoff of this transformer will produce a transient response to the regenerated pulse as given in (1). A spectrum analysis of the transient tail shows that most of its energy occurs in the lower portion of the pass band of the equalized line. Consequently, it will be transmitted over the line to the next repeater with little if any frequency or phase distortion, but will be attenuated by a factor α. This transient at the input of the following repeater may be expressed as

$$T_M = \alpha k_M P_M e^{-bt} \tag{2}$$

where t is again measured from the end of the pulse. Suppose the regeneration of the pulse at the output of repeater N is delayed by time t_1

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* A paper by Rajko Tomovich entitled "Quantized Feedback" was published in the I.R.E. Transactions on Circuit Theory. There are some fundamental differences in the meaning of the term, quantized feedback, as used in these papers.

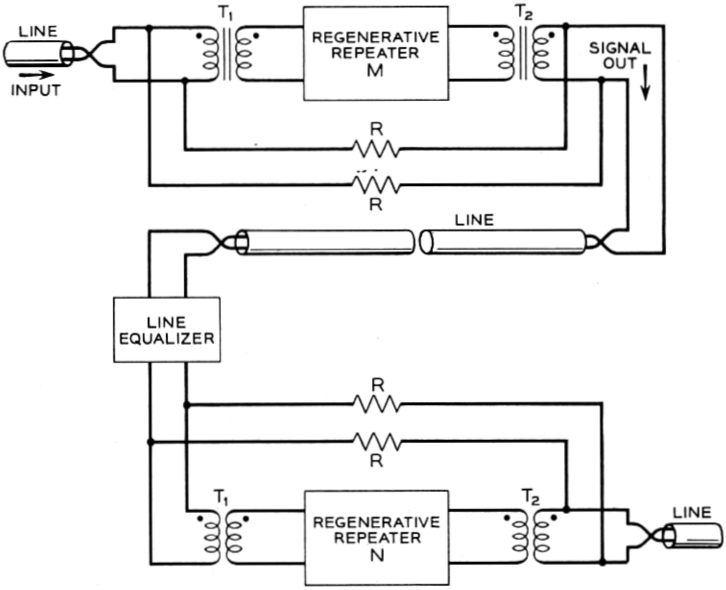

Fig. 2 — Block diagram of a section of equalized line and its terminating regenerative repeaters.

compared to the pulse at the input of the repeater. The transient response of the regenerated pulse after passing through its output transformer† will be

$$T_N = k_N P_N e^{-b(t-t_1)} \tag{3}$$

$$= k_N P_N e^{bt_1} e^{-bt} \tag{4}$$

If the transient (4) is attenuated by factor β and added in opposite phase to T_M through the feedback loop at the input of the repeater, their sum is

$$T_M - \beta T_N = \alpha k_M P_M e^{-bt} - \beta k_N P_N e^{bt_1} e^{-bt} \tag{5}$$

$$= e^{-bt}(\alpha k_M P_M - \beta k_N P_N e^{bt_1}) \tag{6}$$

This can be made equal to zero if

$$\alpha k_M P_M = \beta k_N P_N e^{bt_1} \tag{7}$$

which is accomplished by adjusting the value of β which represents the feedback attenuation introduced by resistances R. If the regenerated

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† It is assumed that the electrical characteristics of the output transformers of all the repeaters are identical. In this case the damping coefficients will be identical for all the regenerated outputs.

output pulses of M and N are identical, then $P_M = P_N$ and $k_M = k_N$ and eq. (6) becomes

$$T_M - \beta T_N = e^{-bt} k_M P_M (\alpha - \beta e^{bt_1}) \tag{8}$$

This expression can be made equal to zero if

$$\beta = \alpha e^{-bt_1} \tag{9}$$

By this means zero wander produced in one repeater can be eliminated at the input of the next repeater. The low frequency distortion of one repeater corrects for the corresponding distortion produced in the previous repeater.

If the electrical characteristics of all the repeater output transformers are identical it is possible to completely remove the effects of the transient tails due to low frequency cutoff.* It is important however that t_1 should not be so large that the feedback pulse occupies the next timing interval. W. R. Bennett has shown that a similar cancellation of transients can be accomplished for more complicated types of low frequency cutoff characteristics. In this case the transient tails will be the sum of a number of exponentials having different amplitudes and damping coefficients. Here the quantized feedback must be provided by multiple loops, of greater complexity.

It may be disturbing at first to observe the resultant sum of the incoming signal and feedback as shown on Fig. 1(e). It should be noted however that the signal is not changed in any way until the repeater has triggered the regenerated pulse, and at the next time slot the tails have been cancelled, so that when the next pulse arrives it too will begin at the zero axis. Tails may also be produced by high frequency phase-loss characteristics. These however, may be removed by proper equalization.

1.3 *Timing In a Regenerative Repeater*

The binary regenerative repeater must not only regenerate the shape and amplitude of each individual pulse but it must also keep them in proper time sequence with other signal pulses. To accomplish this a suitable timing wave must be provided. This timing wave may be transmitted over separate pairs of wires or it may be derived from the signal. In the past it has been common to obtain a sine wave of the repetition

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* It can be shown that, with reasonable differences in damping coefficients, quantized feedback will greatly reduce intersymbol interference even when considering a single pulse. If the contributions from all the transients of an infinite train of random pulses are summed, the resultant interference is further reduced and can be considered negligible.

frequency by exciting a high Q filter circuit from the received pulse train. Short timing pips generated from this wave are used to time the regenerated output pulses precisely. This procedure is far too involved to be used in a simple repeater. If less precision in timing is acceptable it may be accomplished with a minimum of circuitry by use of a sinusoidal wave derived from the repeater output. This is referred to in this paper as "self timing."

Self timing prohibits the use of short timing pips derived from the regenerator output. In this case most of the timing control would be exercised by the filter circuit and little, if any, by the input signal. The direct use of the sinusoidal output of this filter provides sufficient control by the input signal with only a small penalty due to less precise timing.* Self timing also sets certain requirements on the regenerator. If the timing wave is derived from an independent source it can be added to the signal in such a way as to act as a pedestal, lifting the signal above the trigger level. In such a circuit neither the signal nor the timing wave alone can trigger the regenerator. If the timing wave is derived from the output it is obvious that the signal alone must be able to trigger the regenerator, since the generation of a timing wave depends upon the signal triggering the regenerator. A timing wave derived by filtering the output of a random pattern of binary pulses will also have a varying amplitude which could cause variations in repeater noise margins. It is apparent then that self timing output cannot be used as a pedestal in a regenerator. All these objections can be overcome by the use of "inverted pedestal" timing.

Inverted pedestal timing is produced by tying the peaks of the timing wave having the same polarity as the signal pulses to a fixed level by means of a diode. This is illustrated on Fig. 1(f). The timing wave is added to the signal at the input so the sum of the signal, feedback and timing looks somewhat like the wave on Fig. 1(g). The effect of the inverted pedestal timing is to inhibit triggering except in the time interval near the peaks of the timing wave. This permits the signal to trigger the regenerator without a timing wave, yet allows timing control to be exercised as the amplitude of the timing wave builds up. With sinusoidal timing, noise often causes the regenerator to trigger either early or late, introducing a phase shift in the regenerated ouput which will be reflected in the timing wave. Since the timing wave is derived from the code pattern by a relatively high Q tuned circuit, the phase distortion of the timing wave from a shift of a single pulse will be small. With a random dis-

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* E. D. Sunde, Self-timing Regenerative Repeaters (paper being prepared for publication).

tribution of noise the resultant phase shift of the timing wave will be negligible. If the interference has low frequency components, the phase shift of the timing wave may be appreciable but these are slow and consequently will not seriously effect the performance of the regenerator.

2.0 DESCRIPTION OF REPEATER CIRCUIT

The circuit diagram shown on Fig. 3 will aid in understanding the operation of the repeater. The incoming signal after being transmitted over the equalized line is applied through the input transformer T_1 to the emitter of transistor (1). The function of this transistor is to provide gain to the incoming signal. This amplified signal is applied to the emitter of transistor (2) through the blocking condenser C_2. The second transistor functions in a single shot blocking oscillator circuit being biased in the "off" condition through the resistance R_2. When the positive signal exceeds the trigger threshold, a pulse is regenerated by the blocking oscillator. During the pulse period a large emitter current flows through D_1 in the conducting direction. T_2 is the output transformer while transformer T_3 provides the essential positive feedback for the blocking oscillator.

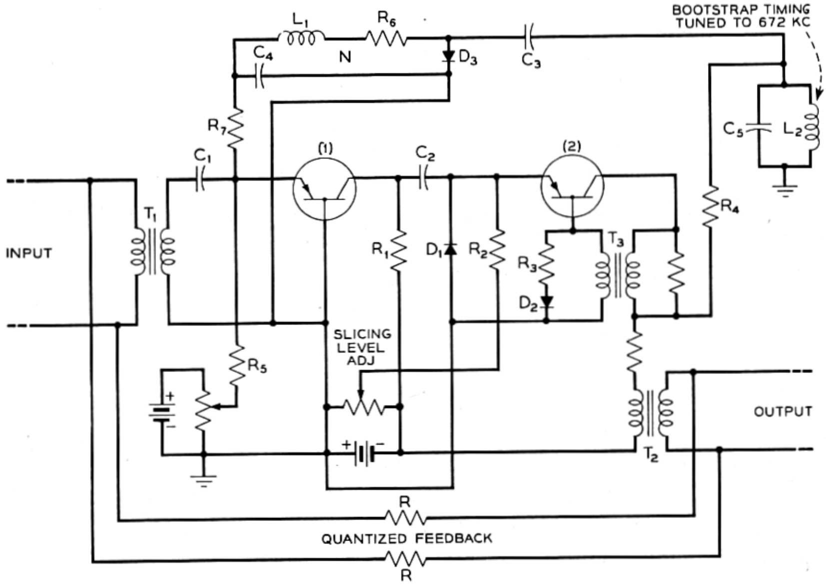


Fig. 3 — Circuit diagram of the regenerative repeater.

2.1 *Inhibiting in Blocking Oscillator*

The secondary of T_3 is connected between the transistor base and ground with the diode D_2 and resistor R_3 in series across it. The combination of diode and resistance across T_3 serves a very important function, the inhibiting of multiple triggering on a single input pulse. During the interval in which the pulse is regenerated a negative potential is applied between the base and ground. A current I_0 flows through the base of the transistor, the diode D_2 being poled to restrict the flow of current in R_3. At the end of the pulse the current I_0 in T_3 drops suddenly to a low value. This current change in the inductive winding of T_3 induces a relatively large potential across the base of the blocking oscillator. The impedance of D_2 becomes low and current flows in R_3 and T_3. The potential across T_3 decays exponentially and with proper circuit values will take the form of a damped cosine wave.

$$E = E_0 e^{-\alpha t} \cos \omega_0 t \tag{10}$$

where t is the time measured from the peak of the pulse. The values of α and ω_0 can be adjusted by varying the inductance the transformer and the capacity and resistance connected across it. E should become substantially zero at or near the next timing interval. The damping coefficient α should be sufficiently large to prevent an appreciable negative excursion of E since this will reduce the effective bias on the repeater and consequently its noise margins. This will be further discussed in the section on the measurements of errors.

2.2 *Quantized Feedback*

The quantized feedback is provided by coupling the input and output transformers by means of resistances R. The fed back pulse must be in the opposite phase compared to the input signal.

2.3 *Timing Wave Circuit*

The timing wave is derived by means of the parallel resonant tank circuit L_2C_5 which is tuned to the signal repetition frequency. The regenerated pulses are applied to this network through the relatively large resistance R_4. The amount of energy added to the network by each pulse as well as the amount dissipated in it is a function of Q. The higher the Q the smaller will be the variations of timing wave amplitude as the average pulse density of the signal train changes. This does not mean that the highest Q will be the most desirable for increased Q means larger, more expensive coils. Higher Q's also produce greater variations in impedance and phase with small changes of resonant frequency which require much closer control of inductance and capacity with temperature. In the circuit described here the Q has a value of about 100 and its operation is quite satisfactory. The tank circuit is coupled through the small condenser C_3 to the diode D_3. This diode ties the positive peaks of the timing wave to ground as is required for inverted pedestal timing. The network N provides the timing delay needed for optimum repeater performance.

2.4 *DC Compensation in Timing Wave*

The timing wave amplitude from the tank circuit is insufficient to allow it to be applied directly to the emitter of the blocking oscillator. Consequently in the interest of circuit simplicity the signal amplifier is used for the timing wave as well. To avoid the complications introduced by dc coupled circuits when close bias tolerances must be maintained, the amplifier was coupled to the blocking oscillator by condenser C_2. This presents a problem as to how to neutralize the charge the dc component of the timing wave builds up on C_2. The means by which this is accomplished can be more easily understood by referring to Fig. 4.

In this figure the time constant of the feedback loop $R_0C_1R_1$, is made large so that substantially equal charges are added to C_1 by each regenerated pulse. In the timing loop this is also nearly true even though noise

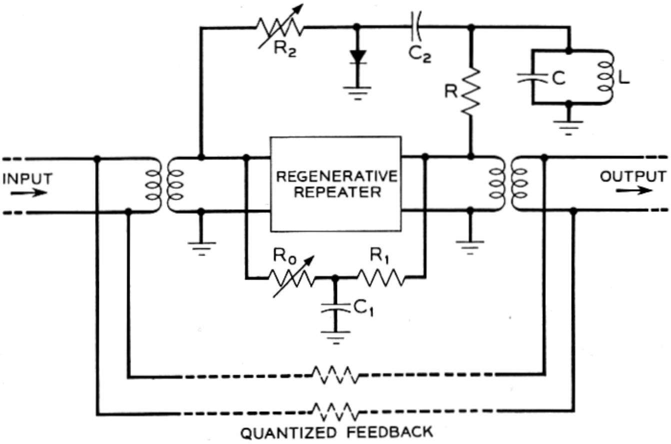


Fig. 4 — Method for maintaining the dc values of timing wave.

may change the phase of individual pulses. The change of amplitude of the sinusoidal timing wave in one pulse period will be

$$\Delta A_T = A_T[1 - e^{-\pi t_m/Q}] \tag{11}$$

where $Q = \omega L/R$ and t_m is the timing interval. In a similar manner the variation of the amplitude of the voltage across C_1 will be

$$\Delta A_C = A_C[1 - e^{-t_m/R_1C_1}] \tag{12}$$

If now R_1 and C_1 are adjusted until

$$\frac{\pi}{Q} = \frac{1}{R_1C_1} \tag{13}$$

and R_0 varied until the amplitude A_C is equal to the average value of A_T, the charge on the interstage coupling condenser should be effectively neutralized at all times. Since both loops are made up of passive elements with common inputs and outputs a single adjustment should suffice even though the pulse amplitude, width, or signal pulse density may vary.

In the repeater circuit shown on Fig. 3 this neutralizing principle is used but is more difficult to see. When a pulse is regenerated, a large emitter current flows in D_1, which produces a sharp negative voltage spike. This voltage adds a charge to C_2 which tends to neutralize the one the timing wave adds to it. The time constant of C_2 and its associated circuit may be made to equal the decrement of the tank circuit and the two amplitudes made equal by adjusting the level of the timing wave. By this means effective dc transmission of the timing wave is achieved through capacity coupling.

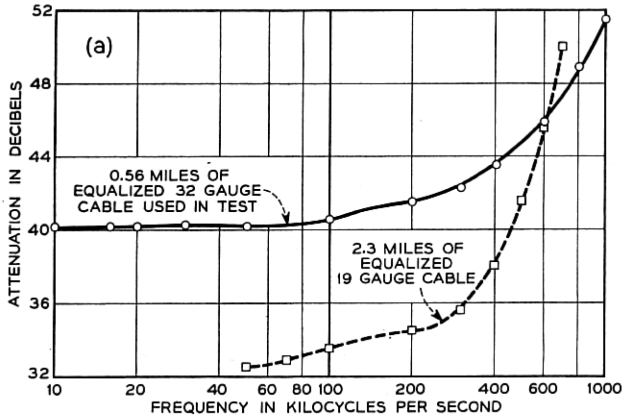
2.5 *Line Equalization*

The line equalizer is not essentially a part of the repeater itself. It is however so intimately connected with the repeater it is logical that they be considered together. One of the important equalizer requirements is simplicity, another, that the impedance seen from the repeater input shall be substantially constant over a relatively large frequency range. This latter requirement comes from the need of transmitting the feedback pulse around the feedback loop to the emitter of the first transistor without too much distortion. The equalizer is not used to equalize the low frequency losses of transformers but only the frequency characteristic of the line. The equalization must be such that the individual pulses are allowed to widen but not enough to cause inter-symbol interference.

A gaussian shaped pulse at the output of the line is one of the most economical to use and can have a maximum span of one timing interval at its base. However, in this case the envelope of a long consecutive sequence of such pulses will show substantially no ripple. It can be readily seen that in such a sequence the only timing control exercised by the input upon the timing wave comes from the first pulse. In the interest of better timing and consequently better repeater performance one should be content with narrower pulses at the repeater input. The resulting ripple of the envelope of a consecutive pulse sequence allows each incoming pulse some control over the repeater timing.

3.0 REPEATER PERFORMANCE

To check the performance of the regenerative repeaters a binary code generator was built having a nominal pulse repetition rate of 672 kc producing an eight digit code. Any code combination from the possible 256 can be selected or the code automatically changed at periodic intervals reproducing all possible codes in orderly sequence. Random codes may also be generated by making the absence or presence of a pulse



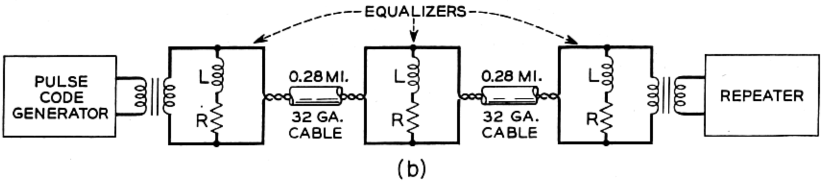


Fig. 5(a) — Equalized characteristics of 19 and 32 gauge line.
Fig. 5(b) — Block diagram of equalizer for 32 gauge line.

in any time slot dependent on the polarity of random noise. The output of the code generator was made substantially the same as the outputs of the repeaters both in shape and amplitude. Two types of transmission line were used, a line from a 51 pair 19 gauge exchange cable and a pair from a 32 gauge experimental cable. The nominal lengths of cable between repeaters was 2.3 miles for the 19 gauge and 0.56 miles for the 32 gauge cable. Fig. 5(a) shows the equalized characteristics for both these lines. The important differences between the two is a greater flat loss with a better high frequency characteristic for the 32 gauge cable. This was advantageous in the study of error production and consequently, the error measurements were all made with this cable. The 19 gauge characteristic represents about the maximum high frequency loss that can be tolerated by these regenerative repeaters.

The performance of the regenerative repeater circuit can best be shown by photographs taken from a cathode ray oscilloscope representation. Plate I shows the effect of the 19 gauge line equalizer. The output pulse (1) transmitted over the unequalized line has become very broad, extending over several timing intervals, which are indicated by small pips along the trace. The addition of the equalizer reduces the width of the received pulse (2) until it is somewhat narrower than the normal pulse interval of the code. Plate II shows a series of photographs taken of the input and output of a repeater with or without interference added at the repeater input.* A signal code at the input of the repeater is shown on (a) and its regenerated output on (b). A sinusoidal interference having a frequency of about 100-kc pictured on (c) is added to the signal as represented on (d). The regenerated output of input (d) is shown on (e). From these it can be seen that while interference does not change the pulse shape or size, it does produce a phase modulation.

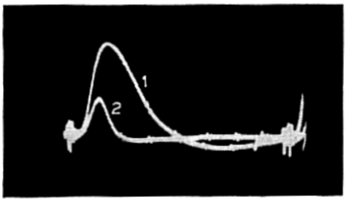


Plate I — Single pulse at output of 2.3 miles of 19 gauge cable. 1 — Unequalized. 2 — equalized.

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* The input signal of this and some of the following photographs was taken with the repeater in an inoperative condition. This was done in order to avoid the resulting complexity that results when both the quantized feedback and timing wave are added to the combinations of incoming signal and interference.

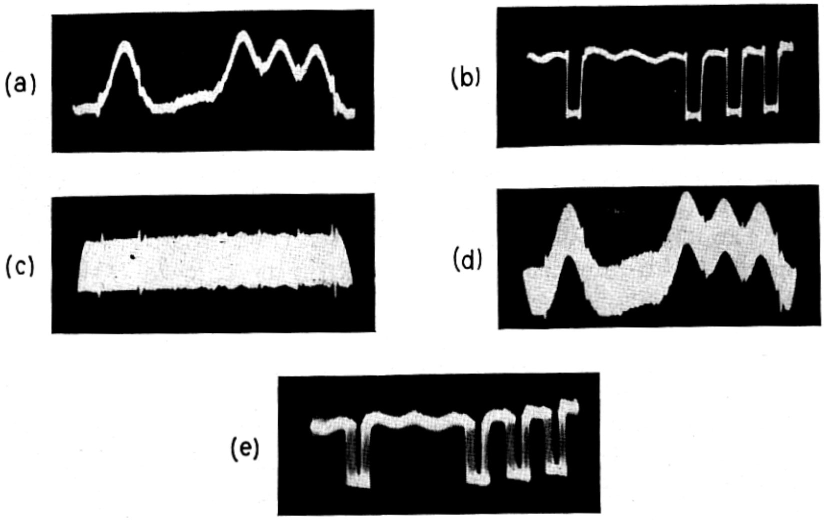


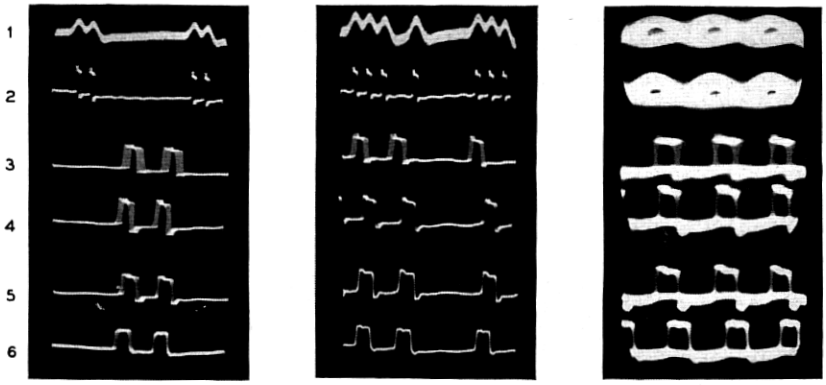
Plate II — (a), repeater input, no interference; (b), regenerated output with input (a); (c), sinusoidal interference; (d), repeater input, signal (a) plus sinusoidal interference (c); (e), regenerated output of (d).

3.1 *Performance of Repeaters in Tandem*

Plate III shows the results when certain phase modulated codes are transmitted through a series of repeaters in tandem. The regenerated signal from each successive repeater is transmitted over 2.3 miles of equalized 19 gauge line. One code which has two out of a possible eight pulses present has most of the phase jitter removed after passing through the three additional repeaters. The other fixed code shown contains four out of a possible eight pulses. The jitter is removed much more rapidly with this code, after passing through two repeaters it is regenerated almost perfectly. The reason for the difference in the regeneration of the two codes is variations in the amplitude of the timing wave. In any period of time the energy delivered to the tank circuit is proportional to the number of regenerated pulses in that interval. The amplitude of the timing wave for a fixed code with two pulses of the eight will be half the one produced by the code having four pulses out of eight present. The average number of pulses in a normal PCM signal will be half the maximum possible pulses. The timing wave should then average the same as that produced by the fixed code having four out of a possible eight pulses present. The phase jitter of the random code should be removed as quickly as it was with this fixed code. This is confirmed by regenerating a noise-dictated random code having the same pulse density expected of a normal PCM signal. The results are shown on Plate III(c). After passing through two repeaters the jitter has been substantially removed as shown by the sharp vertical lines marking the pulses. The thickening of the horizontal lines are produced by transients produced by low frequency cut off distortion. In all these photographs the oscillograph synchronization was obtained from the code generator.

3.2 *Possible Effects of Line Temperature Variations*

The gain and phase characteristics of a particular wire transmission line is a function not only of its length but of temperature as well. To the first order approximation the effect of an increase in temperature may be considered as caused by an increase in the length of the line. In order to better understand the effect of temperature change on repeater performance the following steps were taken; The repeater was adjusted for optimum performance with 2.3 miles of line between it and the preceding repeater and then the length of the connecting transmission line was decreased by about 25 per cent. It was found that for the same interference on the input of the repeater no difference in the performance of the repeater was observed. Plate IV shows a fixed code signal after it has traversed 2.3 miles of equalized cable. Superimposed



(a) TWO-PULSE CODE

(b) FOUR-PULSE CODE

(c) RANDOM CODE

Plate III — (a), set code having 2 pulses out of possible 8; (b), set code having 4 pulses out of possible 8; (c), random code having an average of 4 pulses out of a possible 8.1 (a and b), input signal plus interference; 2 (a and b), regenerated output of 1; 3, expanded section of 2; 4, output of 2nd repeater; 5, output of 3rd repeater; 6, output of 4th repeater. 1(c), input signal alone; 2(c), imput signal plus interference.

on this is the same signal after traversing a 1.75 mile length of line and the same equalizer. Shortening the line results in the transmitted pulses having higher peak amplitudes and narrower widths. Faulty high frequency equalization of the shorter lengths produces the short tail following the pulse. It is interesting to observe that the transient tail due to the low frequency cut off has not changed appreciably as the line was shortened. This is to be expected since it can be shown that the energy of the low frequency cut off transient is concentrated in low frequency end of the transmission spectrum. In this region changes in the length of the line, or changes in the primary constants will result in inconsequential changes in attenuation and phase as is shown on Fig. 6. If the quantized feedback is adjusted for the worst condition, i.e., the highest temperature likely to be encountered, it will not need to be changed with lower temperatures.

4.0 ERROR PRODUCTION BY EXTRANEOUS INTERFERENCE

A knowledge of the performance of a regenerative repeater with various types and amounts of interference added to the input signal is important. Consequently a study of such errors produced in one of these repeaters was undertaken. Two general types of extraneous interference was used in this study. The first is impulse noise, the type which is produced by telephone dials, switches, lightning surges and crosstalk from other pulse systems. The second is sinusoidal noise, the type which come from power line or carrier crosstalk. This interference may affect the regenerated output in a number of ways. It may produce a phase shift or "jitter" in the output; cause a pulse to be omitted; or cause a spurious pulse to be inserted in the signal code. The phase jitter will be largely removed by timing regeneration in subsequent repeaters, but omission and most insertion errors will be carried through the remaining repeaters, causing distortion in the decoded signal.

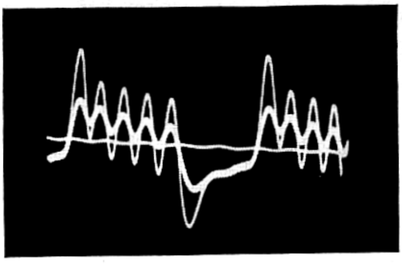


Plate IV — Superimposed picture of the outputs of 2.3 and 1.75 miles of 19 gauge cable with identical inputs.

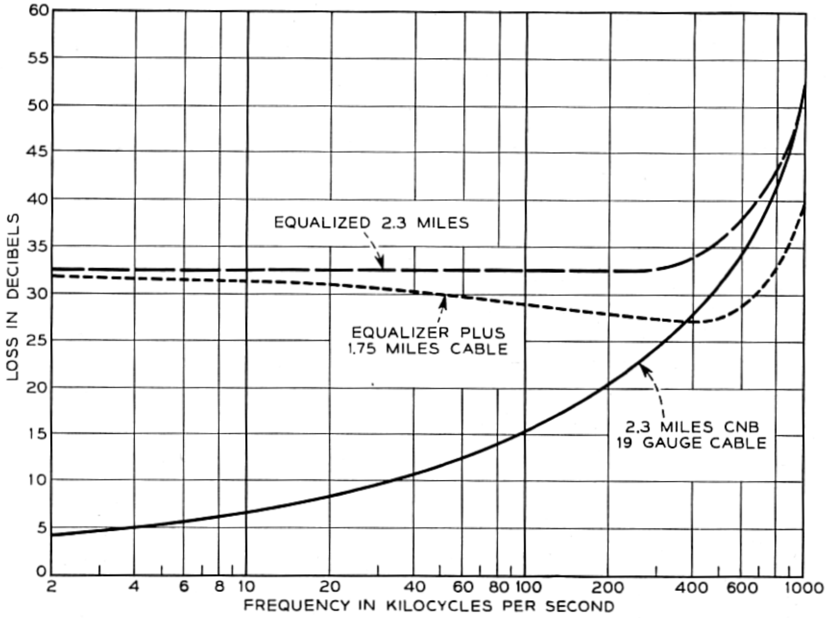


Fig. 6 — Effect of changing the length of 19 gauge line with fixed equalization.

4.1 *Description of Error Detecting and Counting Circuit*

An error detecting and counting circuit was built to count insertion and omission errors. This circuit (block diagram, Fig. 7) is a coincidence detector in which each pulse or space of the repeater input signal is compared to its corresponding regenerated output. As long as the two sources are the same, i.e., having corresponding pulses or spaces, there is no output from the detector. If the two differ the detector produces an output pulse which may be caused to actuate the counting circuit. The code generator as has already been described produces a number of different types of signal codes.

The output of the code generator is transmitted over 0.56 miles of equalized 32 gauge cable to the regenerative repeater under test. Interference is introduced at the repeater input when desired. A portion of the code generator output is differentiated and passed over a delay cable whose delay is substantially that of the section of 32 gauge line over which the signal is transmitted. This delayed signal is regenerated without error by the single shot blocking oscillator A. The width of the blocking oscillator pulses are adjusted to be about half of the total timing interval. The width of the pulses from the regenerative repeater are likewise widened to a corresponding width by blocking oscillator B. Unfortunately a variable phase shift is introduced in the repeater output by interference and by variations in the timing wave amplitude and phase. This variable phase shift prevents perfect coincidence between the outputs of blocking oscillators A and B. An example of phase "jitter" caused by interference is shown on Plate V(a). To overcome this a sharp sampling pip, as shown on the same plate, is provided to enable the detection of the narrow region of coincidence between the two signals. These pips are generated from the repeater timing wave, hence they follow the timing wave phase variations. The regenerated signal pulses also follow the timing wave phase. If the sampling pulse is positioned to fall in the center of the regenerated pulses, it will tend to maintain that position as the timing wave changes.

The gates require a signal pulse and sampling pip to be present simultaneously before there can be an output. This output, then, will have substantially the same shape and position as the sampling pip. When a signal pulse is simultaneously applied to each gate the two outputs can be made to cancel when added in opposite phase as is done in T_1. If however there is a pulse on one gate and a blank on the other, an output pulse will be produced. The polarity of this pulse will depend upon which gate contains the signal pulse. Since the decade counter is

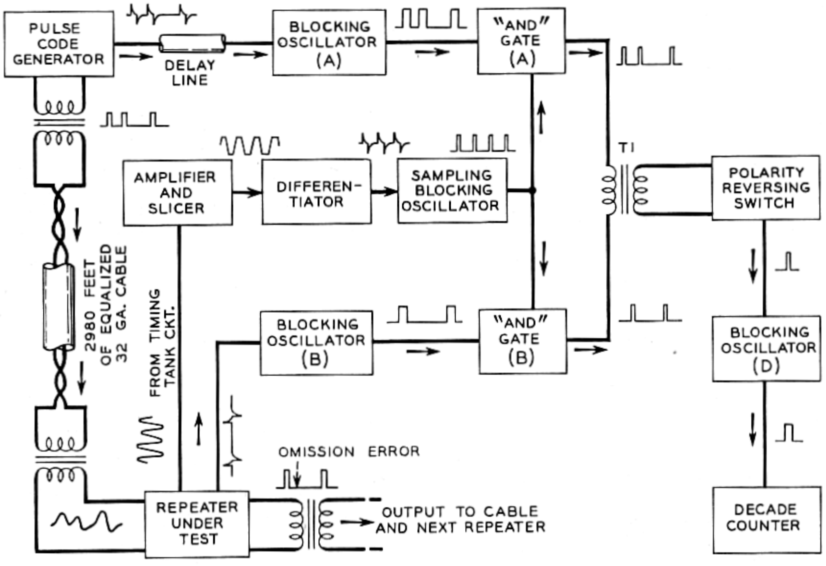


Fig. 7 — Block diagram of error detecting circuit.

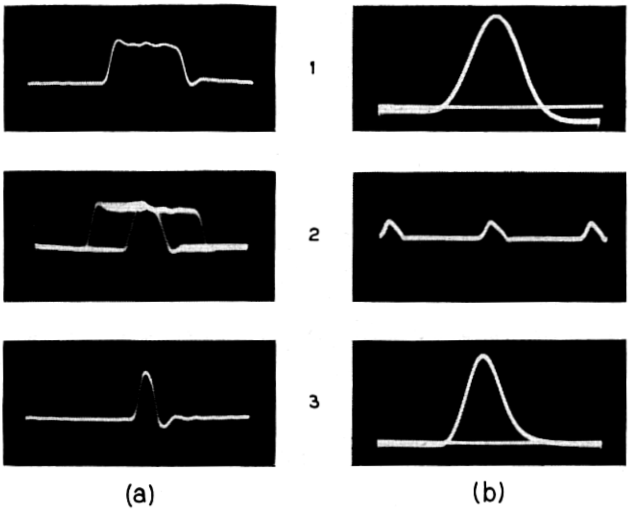


Plate V — (a) with 1, repeater output; 2, jitter on output pulse; 3, sampling pulse. (b) with 1, signal pulse at repeater input; 2, 672-kc timing pips; 3, interference input.

triggered by pulses of one polarity, the reversing switch permits the independent measuring of different types of errors. The counter used in this study has 9 decades capable of counting and recording $(10^9 - 1)$ errors at 10^6 counts per second.

4.2 *Discussion of Impulse Noise Generator*

A study of the noise in cable pairs leading from a central office indicate that impulse noise will cause much of the expected interference on pulse systems. In order to simulate the effect of this type of interference, a generator was built which produces uniformly shaped pulses over a wide range of rates. The polarity of these pulses can be reversed and their amplitude varied continuously from zero to a value exceeding the peaks of the signal pulses. These impulses were introduced into the center of a transmission cable through a high impedance. Plate V(b) shows photographs comparing the impulse with a signal pulse. The repetition rate for the impulse interference used in this investigation was 10^4/sec, which is low compared to the nominal pulse repetition rate of the signal $(6.72 \times 10^5/\text{sec})$. With the relatively large separation between interfering impulses, there is no measurable interaction between errors produced in the repeater. At the same time the impulse rate is high enough to get an excellent statistical distribution in the 10 second interval used in these measurements.

4.3 *Production of Impulse Errors — Nomenclature and Discussion*

To expedite the discussion of impulse errors, the following system of nomenclature is used. Any impulse having the same polarity as the signal pulse is designated as "plus." Those having the opposite polarity are "minus." Two types of errors are produced. First, a spurious pulse may be added to the regenerated signal; this is called an "insertion" error. Second, a signal pulse may be removed, which is called an "omission" error. A "plus insertion" error is a spurious pulse introduced by an impulse having the same polarity as the signal. A "plus omission" error on the other hand is pulse omitted because of a pulse of same polarity as the signal. A "minus omission" error is a pulse omitted because of an impulse having a polarity opposite to that of the signal.

A positive pulse, if large enough, can produce a spurious pulse at any instant of time not already occupied by a pulse. The only requirement for the production of such a pulse is that the sum of the impulse and timing wave exceed the trigger level.* On the other hand, a negative impulse cannot produce a spurious pulse but can only cause a signal pulse to be omitted. If a pulse is to be omitted the sum of its amplitude, the timing wave and the impulse must not exceed the trigger level. It would be expected that the number of plus insertion errors will exceed the minus omission errors. This follows from the fact that a spurious pulse may be produced at any point not already occupied by a pulse. On the other hand if a signal pulse is to be omitted the negative impulse must occur in the time interval occupied by the signal pulse. A positive impulse is indirectly responsible for the positive omission error. When a spurious pulse is produced a short interval of time ahead of a signal pulse, the latter may be removed by the inhibiting reaction of the spurious pulse. There is no apparent way in which a minus insertion error can be produced. This is confirmed by the fact that no error of this type was observed in this investigation. Thus we have three types of errors produced: plus insertion, minus omission and plus omission.

4.4 *Results of Impulse Interference Measurements*

Preliminary measurements of errors as functions of impulse amplitude were made using random code. These measured values, shown on Fig. 8 exhibit many of the expected characteristics. For example the insertion errors are more numerous than the omission and the threshold of the plus omission errors is considerably higher than those of the other two.

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* The trigger level is normally considered to be the negative dc bias applied to the emitter of the blocking oscillator. There are however other components of the bias that will be discussed later.

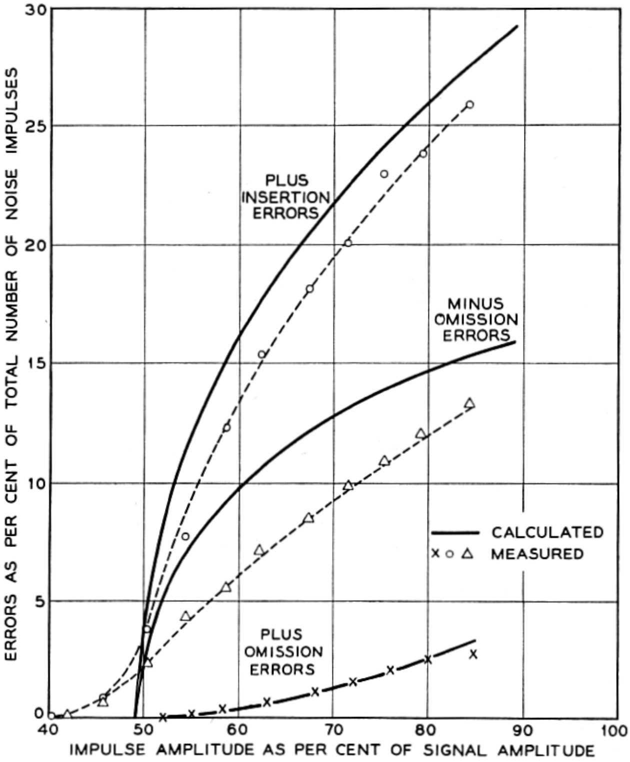

Fig. 8 — Repeater errors as a function of interference amplitude.

On the other hand there are some deviations from the simple theory of a perfect regenerator such as the low common threshold value of the plus insertion and minus omission errors. Some of the differences can be attributed to the extremely sensitive method of measuring errors. Here the maladjustments of timing tank circuit, quantized feedback amplitude as well as other factors which cannot be readily detected by other means are reflected as sources of error. However with care these errors can be made small and the measured values should follow the theoretical values reasonably well.

Most variations from theoretical values are due to changes in the effective bias caused by intersymbol crosstalk. This can be demonstrated by measurements made using set codes. In all these codes the number of pulses equaled the number of blanks but combinations varied from one to another. On Fig. 9 the omission errors are plotted for a fixed impulse amplitude as a function of the number of pulses which

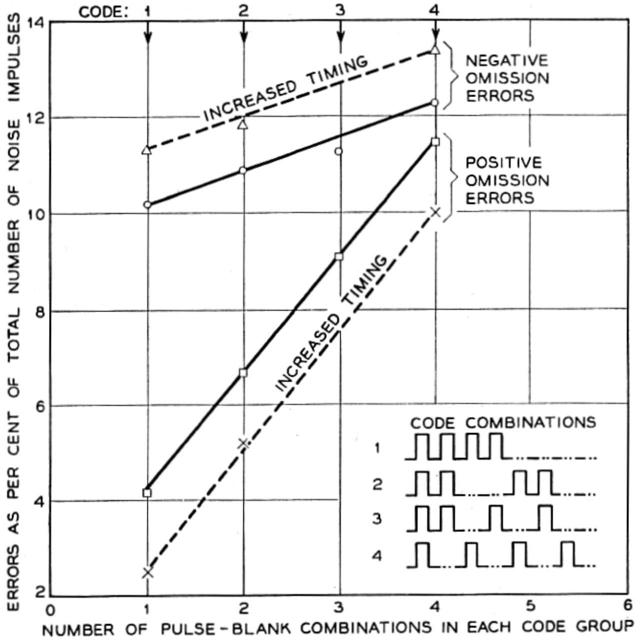

Fig. 9 — Repeater errors as a function of pulse distribution in code.

are followed by a space in the particular code. The codes used for various points on the abscissa are shown on the graph. The omission error curves plotted in this manner are linear. These data demonstrate that the presence of a pulse modifies the trigger level in the next timing interval. This is largely due to the negative excursion of the damped cosine voltage from base to ground in the blocking oscillator. On Fig. 10(a) is shown the circuit of the single shot blocking oscillator used in the repeater. With no timing an incoming signal must overcome bias V_{DC} to trigger the repeater. The solid curve on Fig. 10(b) shows the dc bias with the timing wave added at the blocking oscillator emitter. Fig. 10(c) shows the base voltage when a pulse is produced in the first timing interval. The pulse begins at t_0 and ends at t_1. As previously mentioned the sudden rise of the base and collector impedance coupled with the fall of the current in the transformer windings, produces an inductive voltage surge across transformer T_3 at t_1. The decay of this voltage surge can be controlled by the inductance of the transformer and the damping resistor R_b. This positive decay voltage across the base will inhibit the blocking oscillator from triggering. It is essential that this decay be adjusted so it will inhibit triggering until the following time slot. If the decay transient is a damped oscillation and the base voltage passes through zero at the next normal triggering time, sufficient damping must be provided so the negative excursion is negligible. The dashed line shows how the effective bias at the emitter is modified by this voltage across the base.

Fig. 11 shows the measured values of plus insertion and minus omission errors for two set codes. These are plotted as functions of impulse amplitude. The first code has alternate pulses and blanks while the second consists of pairs of pulses separated by pairs of blanks. With these two curves the error threshold values may be determined from

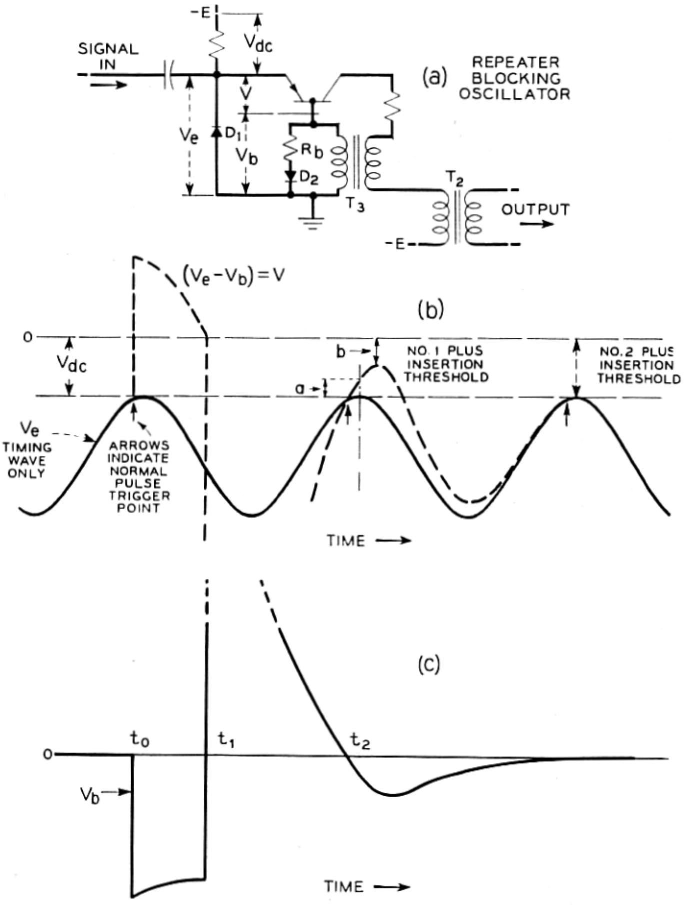

Fig. 10 — (a) Circuit diagram of blocking oscillator showing various components of the effective bias. (b) The effective bias as a function of time. (c) Inhibiting voltage V_b produced by a regenerated pulse.

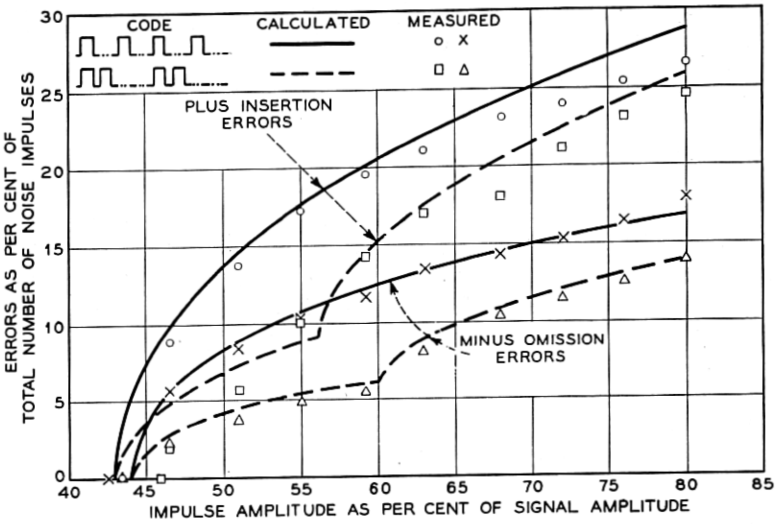

Fig. 11 — Calculated and measured repeater errors for two set codes.

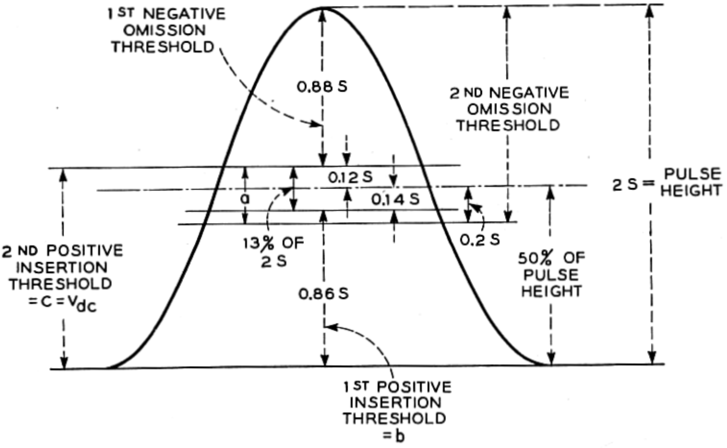

Fig. 12 — Bias levels used in calculating repeater errors.

the points of discontinuity. Fig. 12 illustrates these various error thresholds with reference to a signal pulse. Theoretical curves were plotted using these values and the observed values of timing and signal amplitudes as shown on Fig. 11. It can be seen that very good agreement exists between the measured and computed values.

The separate lower thresholds for insertion and omission errors may be explained from Fig. 10(b). These are caused by the phase shift introduced by the inhibiting voltage to the effective bias compared to that of the timing wave. The omission thresholds are determined chiefly by the maximum signal amplitude. On the other hand the insertion thresholds are determined by the point of maximum trigger bias. There exists then two separate threshold values for a timing interval which follows a regenerated pulse. These values can be measured from points "a" and "b" on Fig. 10(b).

4.5 *Result of Sinusoidal Interference Measurements*

On Fig. 13 are shown the errors produced by sinusoidal interference. Here a 110-kc sine wave is added to the signal and the various types

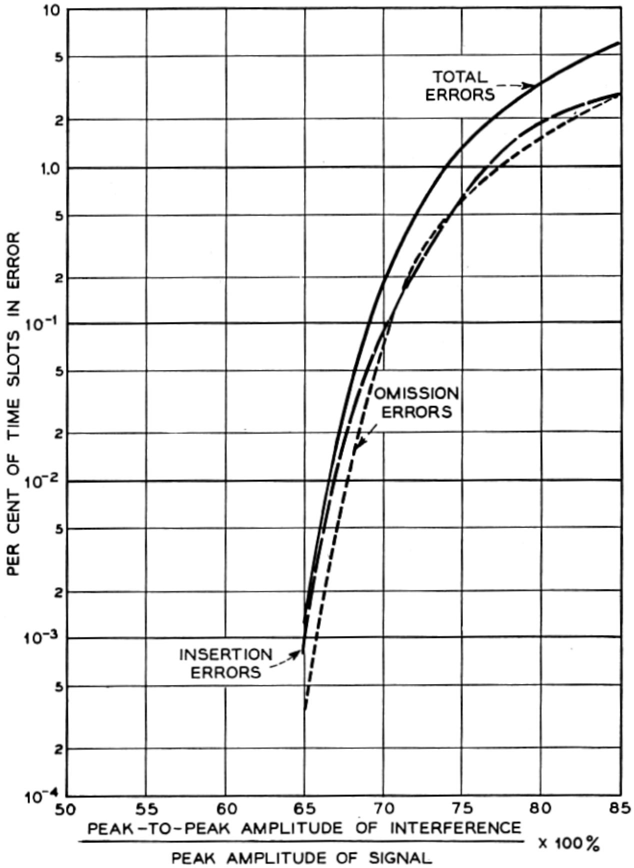

Fig. 13 — Repeater errors as a function of interferences level for sinusoidal interference.

of errors counted. Random code was used in this case and the repeater bias was adjusted to provide equal omission and insertion thresholds. The threshold for this particular case occurred when the peak to peak sinusoidal interference was 63 per cent of the signal amplitude. This is lower than the theoretical maximum which with a constant bias centered at the half amplitude point, would be 100 per cent of the peak to peak signal amplitude. For the bias conditions illustrated on Fig. 12, this percentage would be 86 per cent for the positive insertion threshold and 88 per cent for the minus omission. This becomes apparent when the negative and positive excursions of the interfering sine wave are considered as minus and positive impulses respectively. The remaining loss in the interference margins can easily be due to maladjustments of timing, quantized feedback or inhibiting.

When the frequency of the sinusoidal interference is varied, the number of errors for a constant interference voltage at the blocking oscillator emitter does not change appreciably. However, the input transformer and condenser coupling introduce a substantial frequency characteristic. This reduces considerably the errors caused by power line crosstalk. One of the striking things about the sinusoidal interference errors is the rate at which they increase above the threshold. For example, a change of 1 per cent of the interference amplitude can triple or quadruple the total number of errors.

5.0 SUMMARY

New techniques and devices now make it possible to build practical regenerative repeaters for use in digital transmission. Such a repeater which is suitable for a 12-channel, 7-digit PCM system, is discussed. Simple, inexpensive devices are used to eliminate the effects of distortion due to low frequency cutoff and to provide self timing for the circuit. Experimental evidence is presented which shows the repeater to function as expected.

ACKNOWLEDGEMENTS

I am deeply indebted to J. V. Scattaglia for his aid in this project and to the pioneering work of A. J. Rack on quantized feedback which was of great help in the development of this regenerative repeater. I also wish to thank W. R. Bennett, C. B. Feldman and Gordon Raisbeck for their aid and many valuable suggestions.