MASSACHUSETTS INSTITUTE OF TECHNOLOGY
L I N C O L N   L A B O R A T O R Y

SOME RESULTS ON THE TRANSMISSION OF PULSES OVER TELEPHONE LINES

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ABSTRACT

A description is given of some experiments in which binary coded information was transmitted over leased talk circuit telephone lines. The line characteristics and the pulse distortion caused by them are discussed. A system used to transmit binary digits at a bit rate approximately that of the carrier frequency is described. Some preliminary data on the characteristics of telephone line noise is given with some discussion, supported by measurement, of the error rates involved in the transmission of binary digits.

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With the advent of large scale civil and military information handling systems, and the likelihood that the connections between the elements of any information networks might well be land lines, it is important that these lines be used efficiently and reliably. The subject of the transmission of binary coded data over land lines is one of increasing importance and interest and is the general subject of this paper.

The transmission of pulsed carriers over telephone lines is far from a new technique and has been employed in teletype and facsimile transmission systems for some time. The material which will be presented in this paper is related to the pulsed carrier techniques used in these systems, but is different in that much higher transmission rates with more efficient use of the available bandwidth is contemplated.

The paper is organized essentially in three parts: the first part presents a discussion of some of the more important transmission line characteristics that affect pulse transmission, a description of the kind of pulses transmitted, and some description of the kinds of noise encountered on these lines. The second part describes an experiment which involved the transmission of binary coded information over a long closed loop and discusses the results of this experiment.

TRANSMISSION CHARACTERISTICS

From the measured attenuation characteristics of several lines, as shown in Fig. 1, it is evident that a telephone line is characterized by an increasing attenuation below 300 cycles and an increasing attenuation above about 2200 cycles such that the ratio of the upper half power point of the transmission band to the lower half power point of the transmission band is only about ten to one. Under these conditions it is exceedingly difficult to transmit only uni-directional pulses and one must resort to the use of pulsed carriers. Because of the low upper limit, however, one is forced to use a carrier which is approximately the frequency of the pulse rate and hence one is forced into the situation where the pulse to be transmitted is represented by one to two loops of a sinusoidal carrier. For maximum transmission rate about one loop of the carrier is used and it is with these particular kinds of pulses that the rest of this paper will be concerned. A typical pulse is shown in Fig. 2.

The case of single loops of a sinusoid may, of course, be justified in the classical way by a comparison of the spectrum of a sinusoidal pulse and that of a unipolar pulse of the same duration with the available bandwidth on the telephone line. This is done in Fig. 3 and it is immediately apparent that considerably more of the pulse energy will be transmitted in the first case than in the second.

When a group of these sinusoidal pulses, such as are shown in Fig. 4A, are transmitted over a line the output of the line may be quite badly distorted as shown in Fig. 4B. The cause of these distortions is believed to be largely delay distortion at the upper and lower ends of

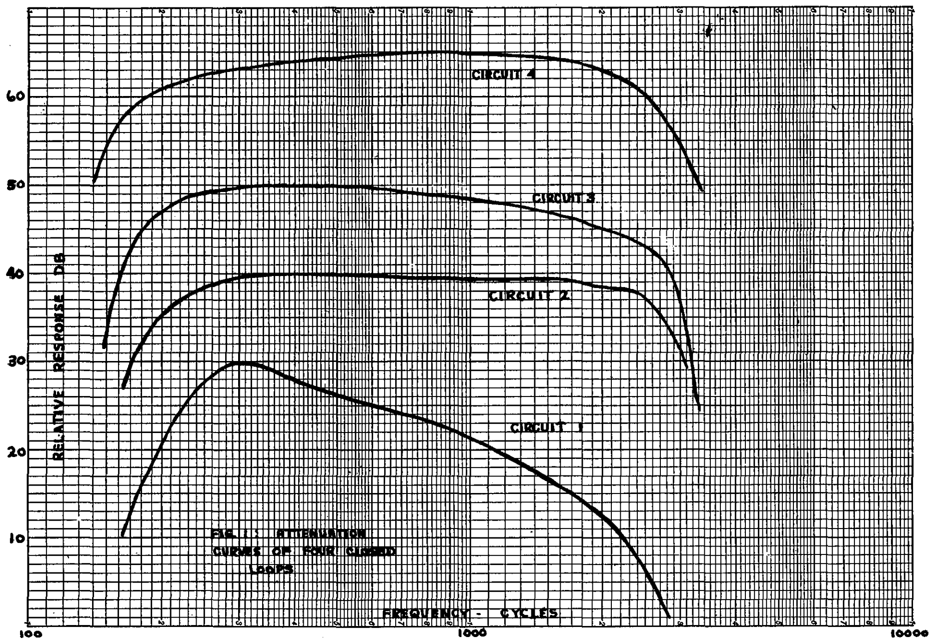


FIG. 1. ATTENUATION CURVES OF FOUR CLOSED LOOPS

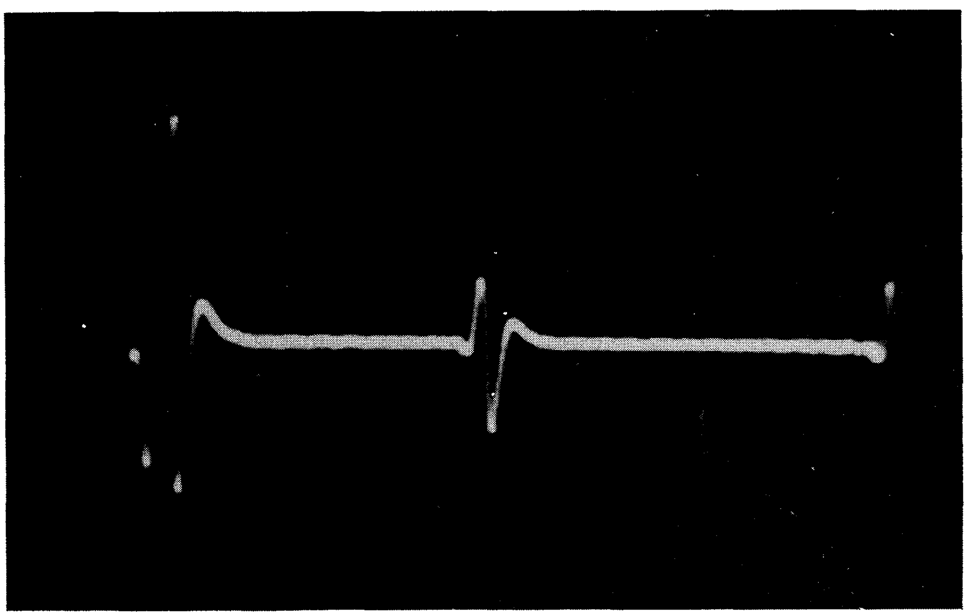
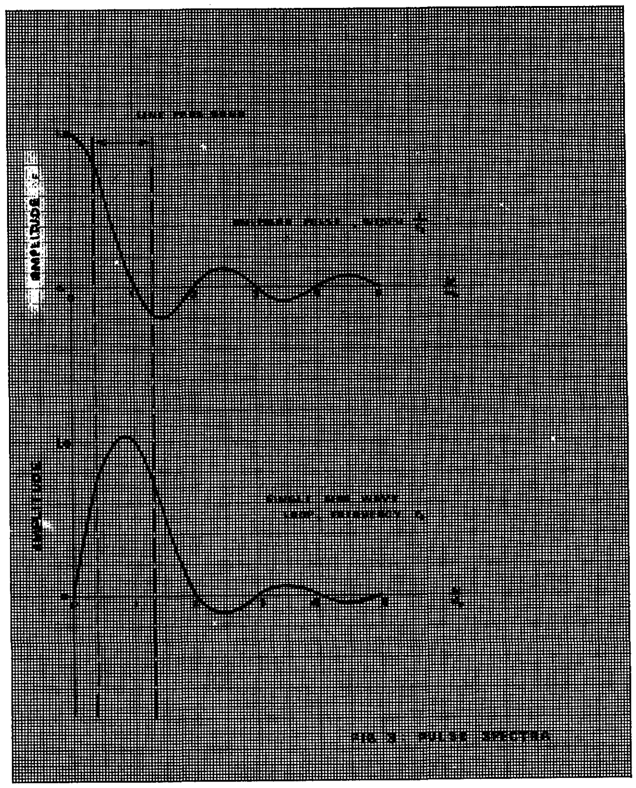


Fig. 2. A typical sine wave loop as transmitted.



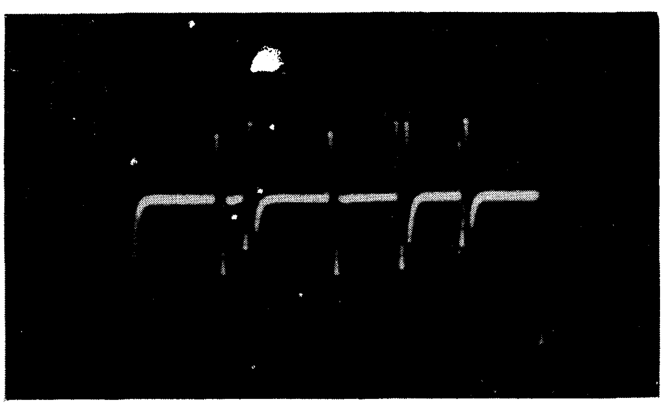


Fig.4A. Several transmitted sine wave loops.

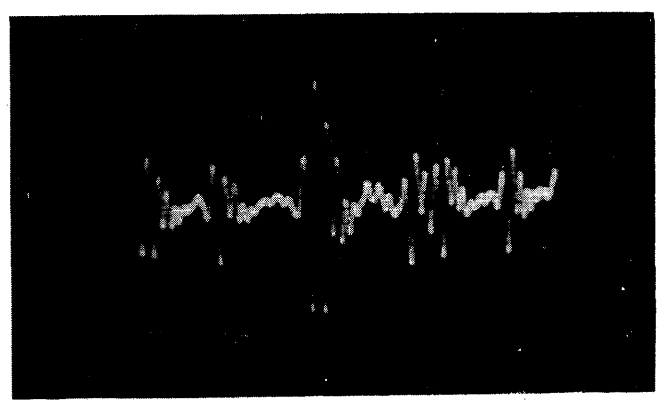


Fig.4B. Several received sine wave loops.

the band. It is informative to examine some simple impulse responses on certain lines in order to explore the response characteristics of the various types of delay distortion. Fig. 5A and Fig. 5B show a simple impulse and the response of about 300 miles of K-carrier telephone line to this impulse. It will be observed that the impulse response is characterized by what is loosely called "high and low frequency ringing". These two types of "ringing" may be isolated by removing from the impulse excitation all components above 1000 cycles, that is, all high frequency components. Under such conditions the output of the line is as shown in Fig. 6, and this is typical of the response of a circuit with low frequency delay distortion. It will be observed that the response starts with a high frequency oscillation which gradually becomes of longer period as it damps out. It is apparent that this is very nearly identical with the theoretical impulse response of a circuit having a hyperbolic phase distortion as shown in Fig. 7A, that is, of an all pass circuit having a phase characteristic given by

$$\phi = \tau\omega - \frac{\omega_0}{\omega}$$

It may be shown that the Fourier transform of

$$\varepsilon^{+j(\omega_0/\omega)} \quad \text{is} \quad \left(1 - \sqrt{\frac{\omega_0}{t}}\right) \quad J_1\left(2\sqrt{\omega_0 t}\right) \qquad 1.$$

and hence the distortion term in the impulse response of our circuit

1. Campbell and Foster, Tables of Fourier Integrals, Pair 654.3.

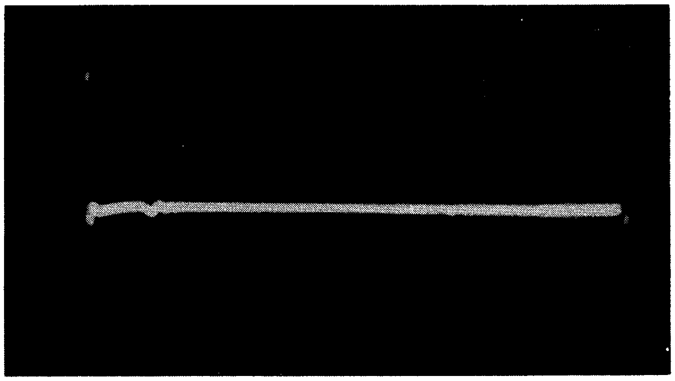


Fig.5A. Impulse impressed on line.

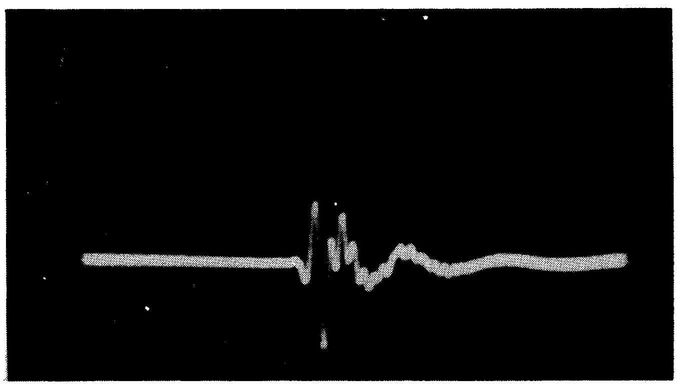


Fig.5B. Impulse received from line.

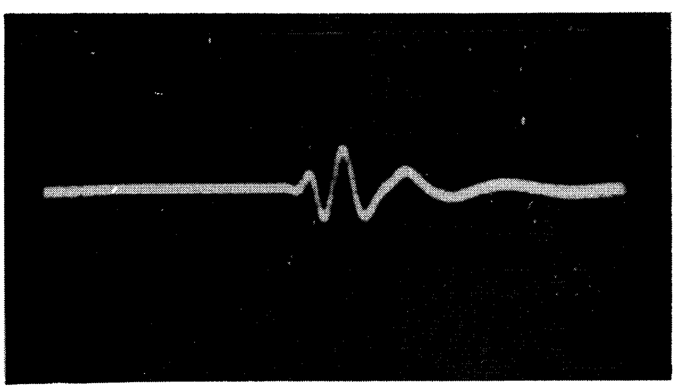


Fig.6. Low frequency response of a line to an impulse.

with pure low frequency delay distortion is

$$\sqrt{\frac{\omega_0}{t}} \quad J_1\left(2\sqrt{\omega_0 t}\right)$$ which is plotted in Fig. 7B.

It is obvious from the phase characteristic that the delay of the low frequency components is much greater than the high frequency components and hence, the highs arrive first as shown in the measured response.

The reverse effect is observed when the impulse used to excite the line is caused to have only high frequency components; thus in Fig. 8A all components below 2000 cycles have been removed from the impulse and the response is as shown in Fig. 8B. This is a typical response of a circuit with high frequency delay distortion such that the low frequency components arrive first and the higher frequencies some time later. A theoretical study of delay distortion at the high end of the pass band has been made by DiToro[2] and a calculated impulse response for an all pass circuit having a phase characteristic of $\phi = \tau\omega + (b\omega)^3$, as given by him, compared quite favorably with the measured response of Fig. 8B. When both kinds of distortion are present the composite impulse response is obtained, Figure 5B.

The conclusion that we reach in all this is that the frequency spectrum below 500 cycles and above 2000 cycles on this particular line is not usable. The exact upper and lower cut-off frequencies certainly vary from line to line and are especially sensitive to line length; however, the numbers just given seem to be representative figures for the lines of moderate length which we have used.

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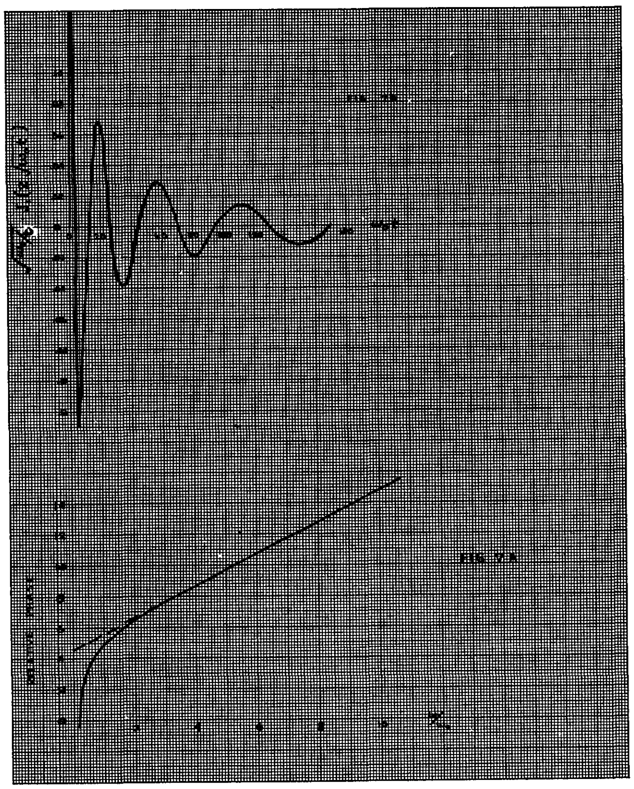
2. M. J. DiToro, <u>Phase and Amplitude Distortion in Linear Networks</u>, Proc. I.R.E. (January 1948).



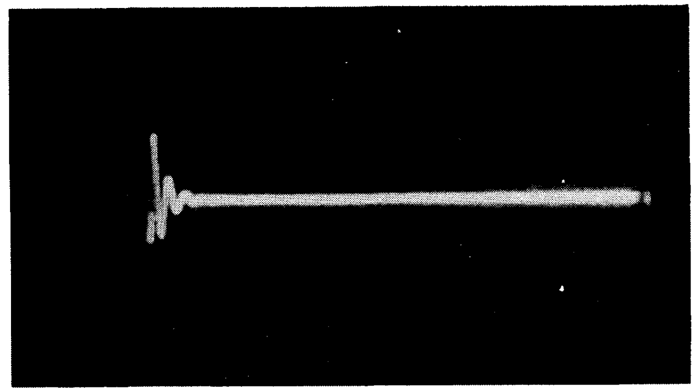


Fig.8A. Impressed inpulse after removal of low frequency.

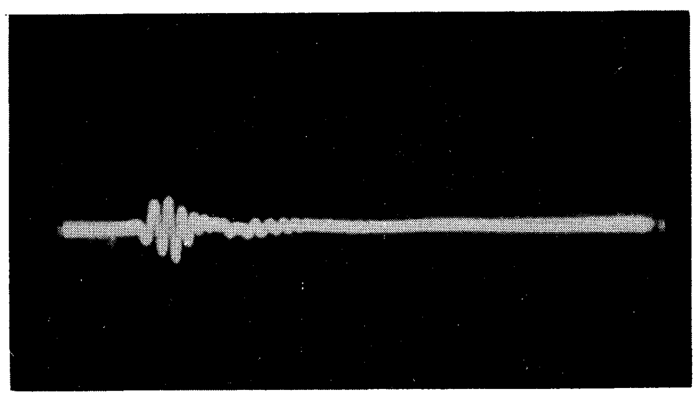


Fig.8B. Response of line to above pulse.

Having concluded that the usable bandwidth of the line lies between 500 and 2000 cycles, it is instructive to present the line impulse response after shaping the impulses by a band pass filter extending from 500 to 2000 cycles. When one does this, the output of the filter is as shown in Fig. 9A and it will be noticed, except for the overshoot due to the filter's high skirt attenuation, the signal resembles our previously chosen single loop of a sinusoid. The response, as shown in Fig. 9B, is relatively undistorted and has the same general characteristics of the filter output although some slight low frequency ringing is apparent.

The measured amplitude and phase characteristics of the line on which these measurements were made is shown in Fig. 10. The increasing delay distortion at the upper and lower ends of the band is quite apparent and it is this which, in our opinion, is primarily responsible for the restriction and determination of the usable bandwidth of the telephone line.

CRITERIA FOR THE TRANSMISSION SYSTEM

The preceding discussion has shown that the usable bandwidth lies between 500 and 2000 cycles. Common usage has indicated that it is desirable to transmit, if possible, with a bandwidth of $\Delta f = \frac{1}{t}$, when f is cycles per second, and t is the duration of the pulse in seconds. This mode of operation renders the receiver's task more simple in detecting the difference between a pulse and a space, since the bandwidth is sufficient to provide adequate pulse definition.

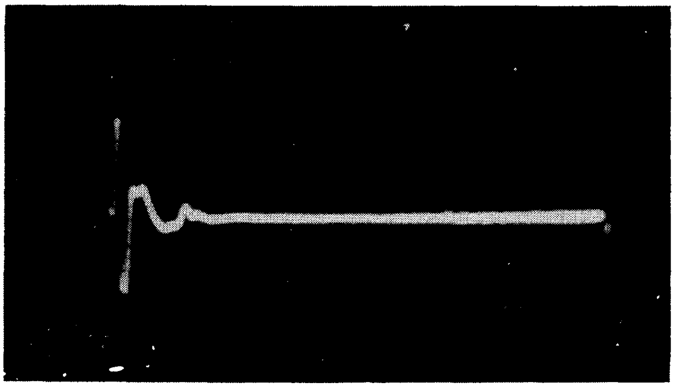


Fig.9A. Impressed impulse after band pass filter.

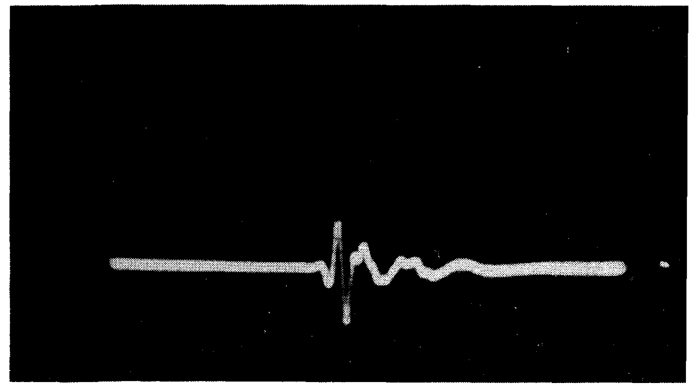
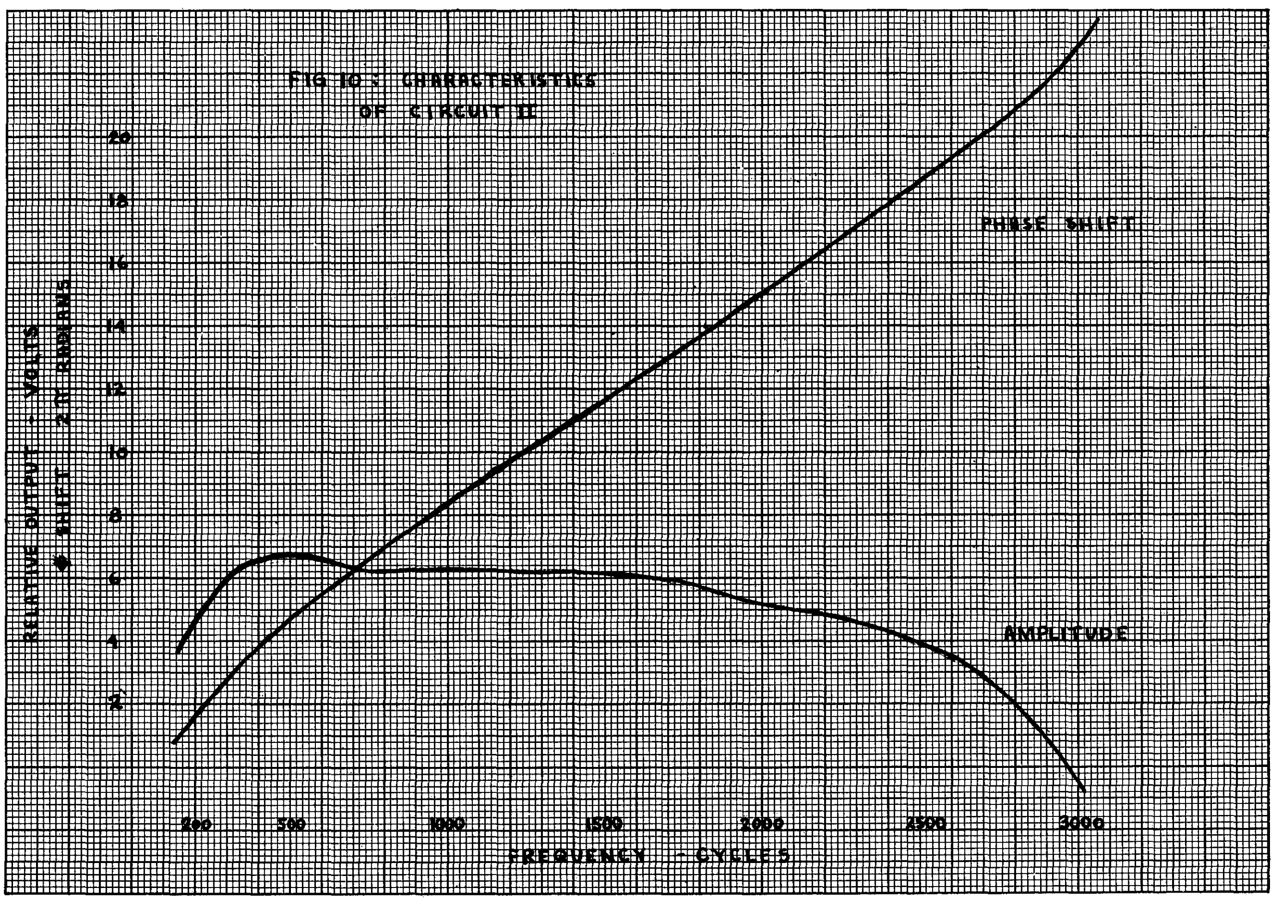


Fig.9B. Response of line to impulse.



Keeping in mind the criteria for good pulse definition, one then weighs double sideband vs. vestigial sideband transmission in the usable frequency band. For minimum pulse distortion, double sideband transmission should be used. Examination of the available bandwidth, however, shows that if double sideband transmission is used, the data rate is restricted to about 800 bits per second in order to satisfy the pulse definition requirements. If vestigial sideband transmission is used, the data rate can be raised to 1600 bits per second, with little degradation of detail between alternate pulses. A penalty is paid, however, in loss of sharpness at the leading edge of the first pulse and the trailing edge of the second pulse. This comes about because the so-called quadrature components which are generated when the upper sidebands are partially suppressed cancel midway between the pulses, effecting good detail between pulses; but no cancellation occurs at the leading and trailing edges, causing poor rise and fall times.[3.] It may be shown, however, that if the no-signal carrier level is not zero, then the effect of the quadrature components become less important, and satisfactory edge sharpness can be obtained giving performance nearly as good as the double sideband case. Since the vestigial sideband transmission is more economical on a bits-per-dollar basis, we have been using a 2000 cps carrier synchronous with the data rate, a maximum data rate of 1600 bits per second, and some non-zero carrier in the absence of signal.

In general, when transmitting pulse type data there are at least two kinds of data to convey; the beginning of a word (a synch pulse) and bits in a word (data pulses), a word being some coherent arrangement of data pulses. Timing may either be transmitted, or the synch pulse may be used at the receiving end to initiate operation of a start-stop oscillator or to lock in a continuously running local oscillator.

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3. S. Goldman, Frequency Analysis Modulation and Noise, McGraw-Hill, pp. 96-98

In the system under discussion the synch pulse is transmitted with twice the amplitude of the data pulses, and timing is also inserted as modulation on the carrier, its amplitude being about 1/10 that of the synch pulse. In accordance with the need for a non-zero carrier for the no-signal condition, about 25 percent carrier, a value experimentally found to be optimum, is also transmitted.

Fig. 11 illustrates the modulated carrier before shaping. Since this signal contains components lying in those portions of the spectrum where serious phase distortion can exist, the signal is passed through a filter having a pass band like that shown in Fig. 12. It may be seen that the response is reasonably flat in the region between 700 and 2000 cps, with a smooth "roll off" below 700 cps and above 2000 cps. Care was taken to restrict the rate of attenuation outside the pass band to avoid ringing caused by the filter itself. Fig. 13 shows a typical transmitted word after shaping on the input to the telephone line.

The transmitted loops of sine wave could be detected directly at the receiving end by means of slicers (amplitude selectors). This direct approach is circumvented on certain carrier type lines where the frequency of the transmitted signal is not kept intact. On these lines the transmitted signal is heterodyned to a high frequency by a local oscillator. The carrier and one set of sidebands is filtered out, and the remaining sidebands sent to the receiving terminals where they are beat against a second oscillator whose frequency is close but not identical to that of the first local oscillator. A sinusoidal pulse received on this type of line shifts constantly in phase, rendering a fixed level amplitude detecting device impractical.

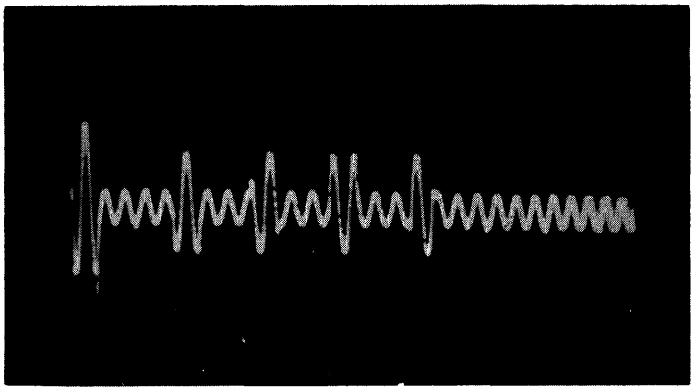
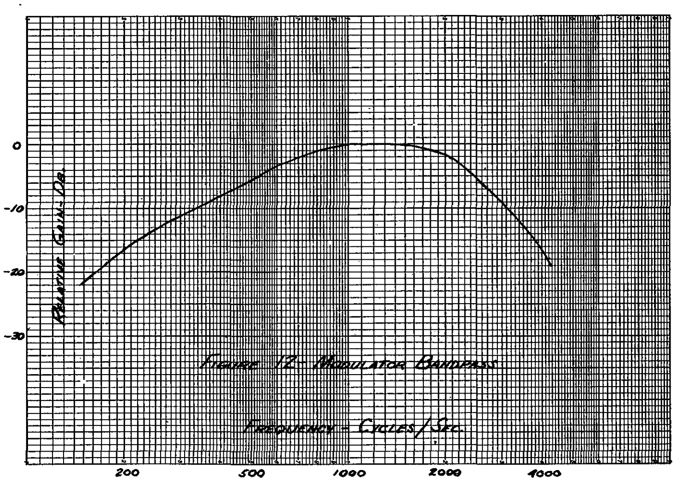


Fig. 11. Modulated carrier before shaping.



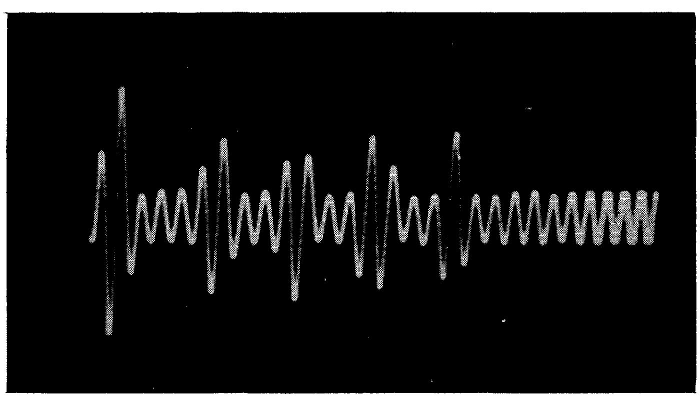


Fig. 13. Modulated carrier after shaping.

To obviate the effect of the frequency change experienced on these carrier types, envelope detection is used. The signal is first full-wave rectified to recover the envelope and to raise the ripple frequency to a value well outside the base band frequency. The rectified signal then is fed to a low pass filter with cutoff at 1000 cps. Since the highest sinusoidal envelope frequency is 800 cps, the envelope is recovered with little distortion. The detected waveform of the transmitted signal in Fig. 13 is shown in Fig. 14 having traversed about 300 miles of cable and carrier line. The detected signal which remains fixed in amplitude and phase, is then fed to two slicers where the synch and data pulses are separated according to their relative amplitudes.

For the case where the carrier frequency is very much higher than the width of the information band, the theory of modulated carriers is well established. In this case, however, where the carrier frequency is about equal to the information frequency, some limiting conditions occur which require investigation. Principal among these is the relationship of the carrier phase to the modulation envelope -- an effect which in conventional carrier systems is negligible or unimportant. Here the ratio of carrier frequency to bit rate is only 5:4, and it was found that the receiving end had greater detection margin if a synchronous carrier was used. The need for carrier synchronization arises from the fact that the pulse spectrum derived from the switched carrier varies appreciably in shape depending on the time of carrier switching, resulting in a variation of the shape and amplitude of the received pulse. When a synchronous carrier is used, the number of phases at which the carrier can be switched is restricted to four, of which two are mirror images of the other two about the baseline.

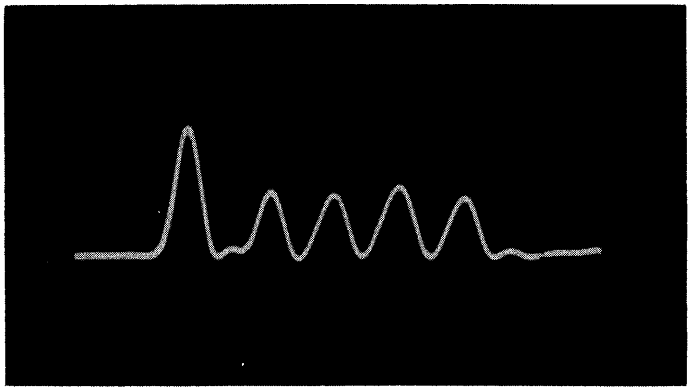


Fig. 14. Detected signal after transmission over Circuit II.

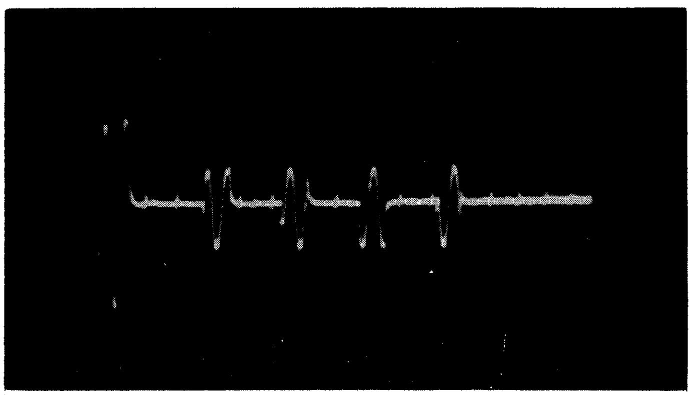


Fig. 15. Four possible carrier phases in transmitted signal.

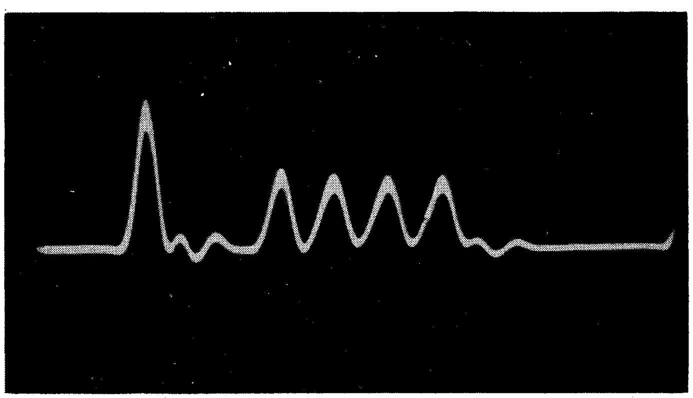


Fig. 16. Received pattern when a non-synchronous carrier is transmitted.

Since full wave detection followed by smoothing is used at the receiving end, there is only a barely discernable difference when a detected pulse derived from one of the four carrier phases is compared to a pulse derived from another carrier phase. Fig. 15 illustrates the four possible carrier phases in the transmitted signal, and Fig. 14 is the received signal for this transmission. Fig. 16 shows the same received digit configuration integrated over several sweeps where a non-synchronous carrier was used in transmission. The changing pulse amplitude can be seen clearly in the blurred trace.

NOISE EFFECT MEASUREMENTS

Broadly speaking, observed noise on telephone lines can be categorized into two types; bandwidth limited white noise and impulse noise. At normal operating levels (0 dbm referred to the synch pulse) we have found impulse noise to be more troublesome.

It will be recalled from the beginning of this discussion that an impulse, after being shaped by the line, resembles very closely the form of a legitimate bit of data. Consequently, a noise impulse after being shaped by the transmission characteristics of the line may appear as a false bit of data, or it may cancel a real bit of data depending on the phase and occurrence time of the impulse. Fig. 17 illustrates the case of a noise impulse appearing as a false bit, and also shows cancellation of the carrier.

To obtain some measure of reliability of transmission in the presence of noise, a test was set up on two closed loops whose amplitude characteristics are shown as circuits 1 and 2 in Fig. 1.

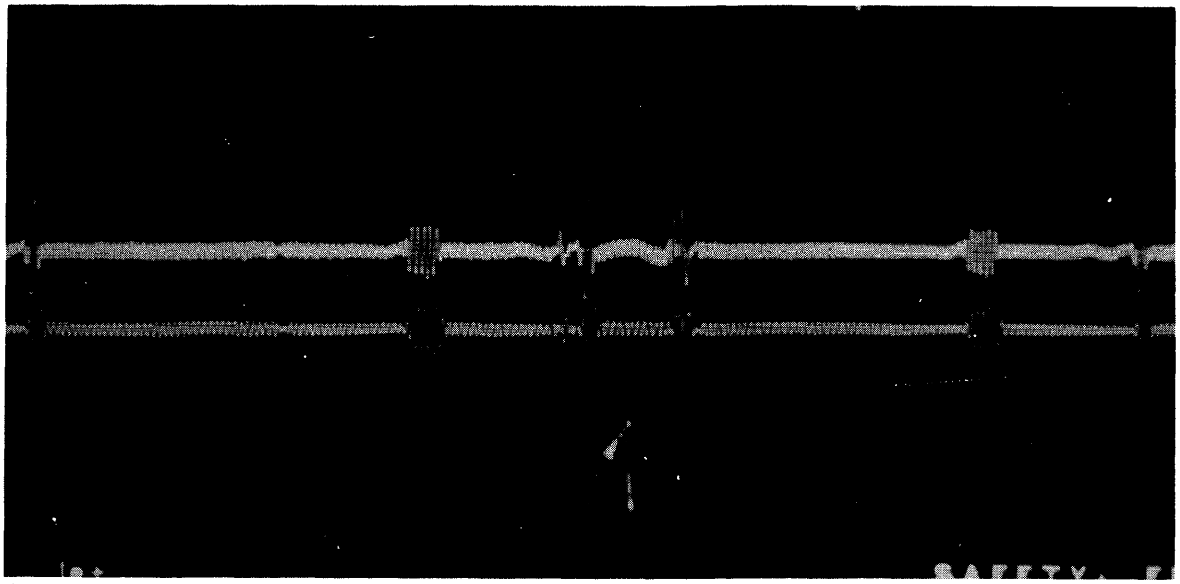
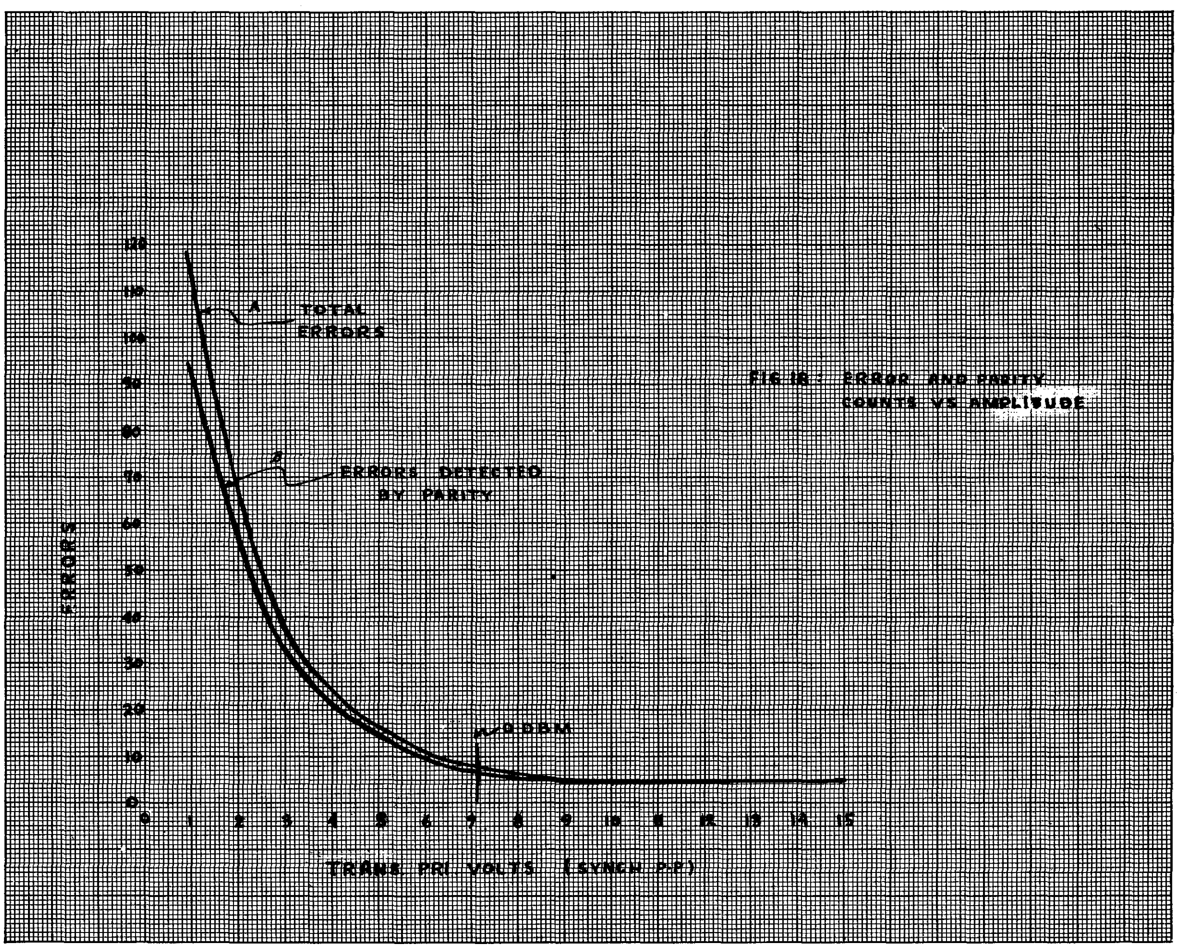


Fig. 17. Noise pulse as false data bit; and noise pulse cancelling carrier.



The tests were conducted as follows; an arbitrary 31 bit word, as illustrated in Fig. 13 was transmitted repeatedly. As may be seen, a word was composed of a synch pulse (the larger pulse) followed by the data pulses containing the desired information. At the receiving end the information on the line was decoded to a pulse form, and compared bit by bit with the transmitted data. If a single bit in the word was in error, i.e., if comparison showed that a bit was not identical with the transmitted bit in a given time slot following the synch pulse, then the entire word was considered in error. As a matter of interest, a single error detecting parity check was also used, i.e., the sending end was arranged so that the number of transmitted pulses was always even. By determining whether the receiving end saw an even or odd number of pulses in a word, one is thus provided with a partial means for detecting an erroneous word. The results of the test may be summarized as follows:

	Circuit 1	Circuit 2
Words Transmitted/hr.	180,000	180,000
Avg. Errors/hr.	2688	6.5
Avg. Errors Detected by Parity/hr.	2304	3.8
Undetected Errors/hr.	384	2.7

It is immediately apparent from the above tabulation that a vast disparity in noise characteristics can exist on various lines, giving either very good results as exemplified by Circuit 2 above, or very bad results as shown by Circuit 1. It should be noted, however, that the results obtained from Circuit 1 are not necessarily characteristic of telephone lines in general, since the line used was selected for its nosiness to provide a ready source of test data. From visual observation of transmission on many other lines, we estimate that the majority of lines would provide an error rate well within the order of magnitude exhibited by Circuit 2.

It was observed that in most cases, the impulse noise was much greater in amplitude than the background noise. To get some measure of the amplitude distribution of the impulse noise, an error rate measurement was made while varying the overall amplitude of the signal on the line. A single bit error detecting parity was used in this test also. The curves yielded by this test are of interest and are shown in Fig. 18.

It may be seen from Curve A, a plot of error rate vs. signal amplitude, that the slope levels off rapidly. Since the curve is nearly flat at +6 dbm, two conclusions may be drawn: (1) that a large part of the impulse noise exceeds at least twice the data pulse amplitude, and (2) that an increase in signal level on the line over 0 dbm would provide little decrease in the error rate. Curve B is a plot of errors detected by parity vs. signal amplitude. Note that this curve follows Curve A very closely in the large signal amplitude region, but diverges in the small amplitude region. The implication here is that for large signal operation the troublesome noise effects are caused mostly by single impulses, to which the parity is sensitive, whereas when the signal approaches the level of the white noise, the nature of the noise becomes more random, causing two digit errors as well as single digit errors. It should be emphasized that these results are based on tests made on two circuits and are therefore not conclusive. Tests are being made at the present time by representatives of the Bell system on a number of lines to corroborate or disprove the above results.