The Lenkurt® Demodulator

NEWS FROM LENKURT ELECTRIC

VOL. 9. No. 7 JULY, 1960

Delay Distortion

—— Cause and Cure

Within the last decade, high-speed data transmission has become one of the most vital services provided by the great communications networks. The explosive growth of electronic data processing and the construction of elaborate defense warning networks from existing telephone facilities has placed new importance on some rather old transmission problems. One of the most important of these is delay distortion. This article reviews some of the more important aspects of delay distortion — why it occurs and how it may be overcome.

For many years, the quality of a communications channel (or even a high-fidelity music system) has been judged by its ability to reproduce the moment-to-moment level or amplitude of the original signal. Since both the communications system and the hi-fi set have only to satisfy the ear of a listener, amplitude response has proved to be a good measure of performance. When pictures were first transmitted by wire about 1930, it was discovered that a channel having excellent amplitude response might be quite unsatisfactory for picture transmission. The harmful effect, called *phase distortion*, and now more commonly called *delay distortion*, resulted from the phase-shift characteristics of the transmission path, and had little relation to the amplitude response or fidelity of the transmission path.

Since then, other communications services have sprung up which are equally vulnerable to this type of distortion—facsimile, television, and high-speed data transmission are typical. All types of transmission may cause delay distortion, with the exception of radio

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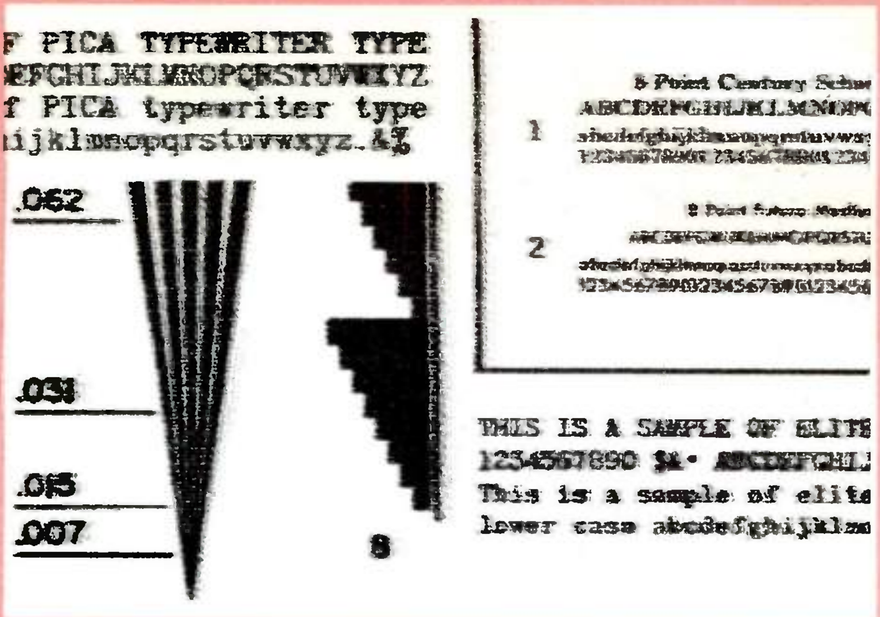


Figure 1. Actual sample of facsimile transmission over a circuit not corrected for delay distortion. Note the fine echoes following each transition from black to white or white to black. This same effect occurs in high-speed data transmission, causing errors to increase.

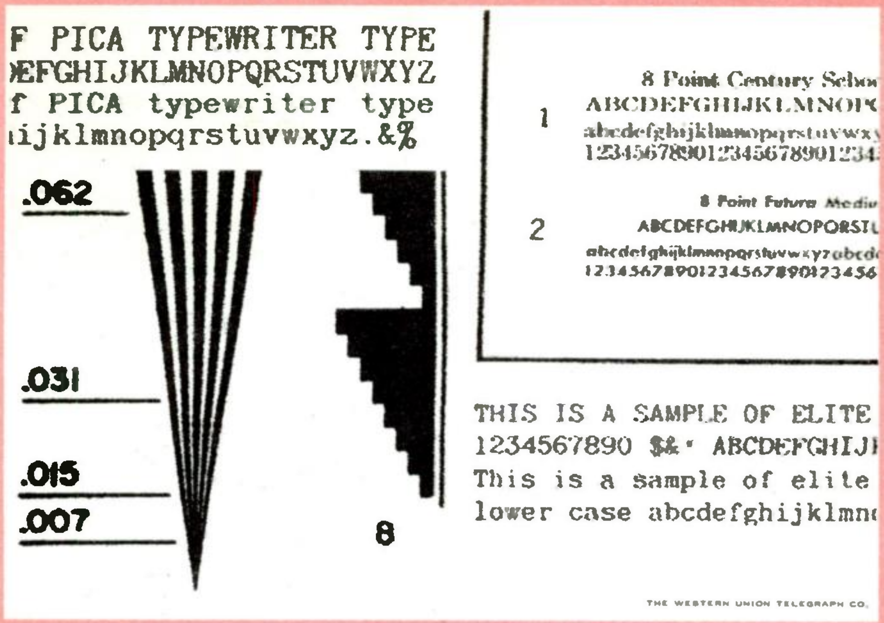
propagation through free space. Even radio does not escape, however, since the tuned circuits in transmitter and receiver may provide an abundance of delay distortion.

What is Delay Distortion?

Electricity travels 186,000 miles per second in free space. Electrical signals do not travel this fast through communications channels, however. Messages may travel over loaded telephone cable as slowly as 20,000 miles per second, and rarely travel faster than about 100,000 miles per second over a microwave carrier system. These remarkably slow velocities result from the nature of the communications equipment or the transmission path.

A telephone line behaves like a band-pass filter, particularly if inductive loading is employed to extend frequency response. Carrier systems use very sharp filters to separate one channel from another, and the tuned circuits in a radio receiver serve the same purpose. All these filters and filter-like elements introduce phase shift, and phase shift is the source of delay.

The unavoidable capacitive and inductive reactances associated with various types of communications channels introduce delay because they require a definite time to react to different frequencies. For instance, a capacitor does not charge instantly. It requires a definite time, depending on the capacitive reactance of the capacitor and the applied voltage. Since capacitive reactance varies with frequency, the charging time will also vary with frequency. Similarly, an inductance requires a cer-



Transmission is greatly improved when the delay distortion present in the transmission medium is corrected by delay equalizer. Lines and other fine detail are reproduced much more sharply. The ability to transmit finer detail by equalizing delay is similar to higher speed data transmission.

tain amount of time to build up its inductive field, and this also varies with frequency.

The slowing down of a signal in its passage through a communications channel is of little importance. Delay becomes a problem only when it interferes with the ability of the receiver to understand the message. In the case of speech, delay distortion causes little interference with the intelligibility of the message. Facsimile, high-speed telegraphy, and data transmission are extremely vulnerable to delay distortion, however. Such transmissions consist of pulses—rapid transitions between two or more states, whether these be voltages, frequencies, or phases. Regardless of the method of transmitting marks and spaces, the higher the transmission speed, the more abrupt must be the transitions between the information-carrying states. This abruptness inherently requires a greater band of frequencies for successful transmission. If pulses are transmitted through a channel which does not have enough bandwidth for the transmission speed, the receiver output will be garbled and degraded, perhaps not even identifiable.

The reason for the increased bandwidth lies in the nature of a high-speed pulse. When the pulse begins or ends, the rapid change causes signal energy to be distributed over a wide band of frequencies on either side of the pulse frequency. The exact amount of energy appearing at each frequency on either side of the pulse frequency depends on the nature of the pulse—its shape, rise-time, etc. If, for any rea-

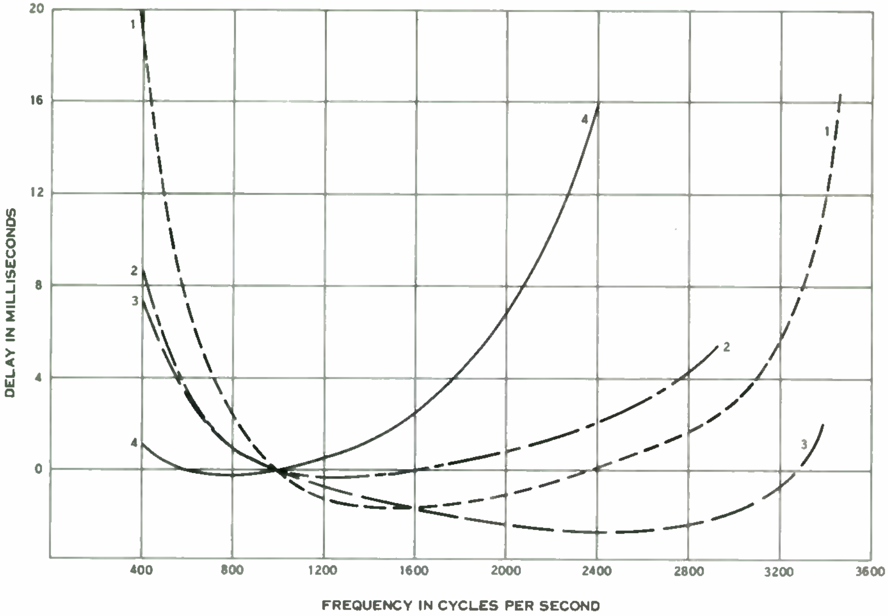


Figure 2. Comparison of the envelope delay in some typical telephone channels. Curves 1 and 3 represent the delay in several thousand miles of toll-quality carrier. Curve 2 shows the delay produced by 100 miles of lightly loaded cable, and Curve 4 shows the delay in 200 miles of heavily loaded cable.

son, some of the energy from either sideband is displaced in time or amplitude from the original value, the pulse will be distorted when it is "put back together" by the receiver.

If the transmission path delays some of the frequency components more than others, the pulse will be distorted. If the delay is great enough, some of the energy from a signal pulse may actually be delayed enough to interfere with the following pulse, thus destroying information carried by both pulses. It becomes evident, therefore, that delay introduces distortion only when various frequencies in a communications channel are delayed different amounts of time.

Phase Shift

The phase and frequency of a signal are, by definition, inseparable. In fact, a good definition of *frequency* is *the rate of change of phase with respect to time,* or $d\phi/dt$, where ϕ is the phase shift (usually in radians — π radians equal 180°, two π radians equal one cycle) and t is time in seconds. Thus, it follows that the more the phase of a signal is shifted in passing through a channel, the more time is required for it to get through the channel. Where the phase shift is known, the phase delay of a single frequency is

$$time = \frac{phase\ shift\ (radians)}{frequency\ (radians\ per\ sec.)}$$

This is usually expressed

$$t = \frac{\phi}{\omega}.$$

It is important to note that in practical systems, phase delay, as expressed above, is applicable only to single, steady-state frequencies.

In an ideal system, phase shift is directly proportional to frequency. All signals passing through such a system would be delayed equal amounts, regardless of their frequency. Unfortunately, phase shift in a communications channel is never linear. The capacitances and inductances which are inevitably present in all communications channels are never perfect. Although a pure capacitance would shift the phase of an applied signal exactly 90°, losses in the capacitor reduce this phase shift a small amount, the exact amount varying with the signal frequency and the nature of the capacitor. A similar departure from ideal performance is observed in inductances of all types. In practical systems, these variations from ideal performance add up, with the result that the overall phase shift characteristic may look like that shown in Figure 3.

Envelope Delay

Whenever a complex signal (such as a modulated or keyed carrier frequency) is transmitted, the relationship given above for phase delay no longer holds true, unless the system is perfectly distortion-free. Since phase shift is always non-linear in actual systems, some of the component frequencies undergo more phase shift than they would in a linear system. As a result, they travel through the system slightly slower than some of the other frequency components.

For simplicity, assume that the complex signal consists of only two component frequencies. Added together, the two frequencies form a beat-frequency or modulation envelope. Since the two component frequencies travel at different velocities through the channel (because of non-linear phase shift), the relationship between them constantly changes, and the modulation envelope travels through the channel at a third velocity. If phase shift were linear, both component frequencies would travel at the same velocity, and there would be no displacement of one frequency with respect to the other, and no independent delay of the modulation envelope or *envelope delay.*

The more non-linear the phase shift, the greater the envelope delay. In other words, the greater the *rate* of change of phase shift, the more envelope delay will result. The delay in seconds

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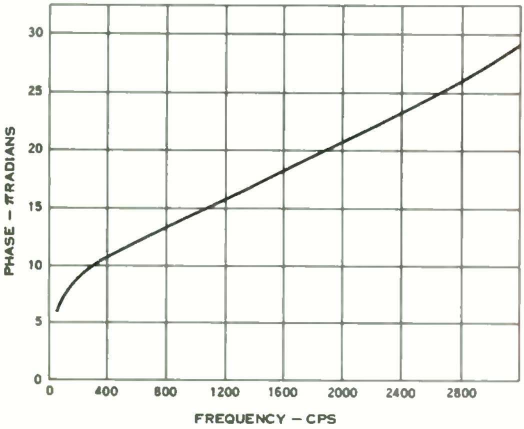

Figure 3. Typical phase shift characteristic of 100-mile carrier telephone circuit. Note that at no point is the curve straight.

GLOSSARY OF TERMS

Delay distortion phenomena have been of general interest only in the special fields of high-speed telegraphy and facsimile until very recently. Because of this general neglect, there is a wide variation in the use of terms and definitions. The definitions below represent the most common usages, and are in accord with definitions which have been published by the Institute of Radio Engineers: IRE Standards on Facsimile: Definition of Terms, 1956 (56 IRE 9.S1).

ABSOLUTE DELAY — The total time required for a signal to pass through a network or channel. Where the delay in a channel varies with frequency, a common meaning for the *absolute delay* of the channel is the *least* delay found in the channel passband; otherwise, *absolute delay* refers to the actual delay encountered at a specific frequency. In Figure 2, the *absolute delay* at frequency f_1 is t_2; the absolute delay of the channel is t_1. *Absolute envelope delay* at any frequency is $\frac{d\phi}{d\omega}$, and *absolute phase delay* is $\frac{\phi}{\omega}$, where ϕ is phase shift in radians and ω is frequency in radians per second.

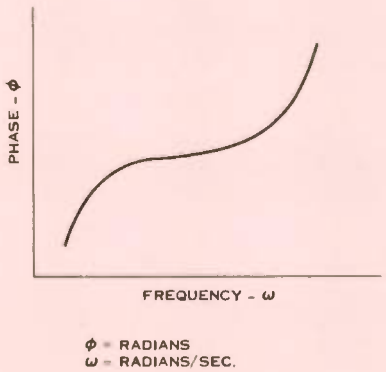

Figure 1.

DELAY DISTORTION — The distortion which results when some portions of a pulse or wavetrain are delayed more than others. Although there are several forms of *delay distortion*, only *envelope delay distortion* is of general interest or importance. *Envelope delay distortion* of a channel is sometimes expressed as one-half the *relative delay* (as defined below).

DELAY EQUALIZER — A network which is designed to make the *phase delay* or *envelope delay* essentially constant over a desired frequency range. Ideally, such an equalizer introduces compensating delay at certain frequencies without affecting the amplitude response of the circuit or channel. Because perfect, lossless reactances are not available, some amplitude disturbance will occur in practical circuits.

DIFFERENTIAL DELAY — The difference in delay of two frequencies of interest in a band or channel. Also, see *relative delay.*

ENVELOPE DELAY — This is the time delay of the modulation *envelope* of a signal in passing through a channel or network. For example, if two sine waves of slightly different frequencies are transmitted through a channel at somewhat different velocities, the resulting beat-frequency peaks and valleys will travel at a third velocity called the *group velocity.* The transit time of the *envelope* through the channel is the *envelope delay.* The phase of the envelope will be shifted by the difference in phase shift of the two component frequencies. The envelope delay in seconds, in the case of a complex wave, is $\frac{d\phi}{d\omega}$, where ϕ is phase shift in radians, and ω is frequency in radians per second.

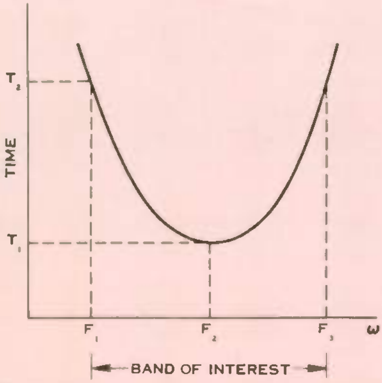

Figure 2.

GROUP DELAY—The same as *envelope delay.*

LINEAR PHASE-INTERCEPT DISTORTION—A special case of *phase delay distortion.* This type of distortion would appear in a system having linear phase-frequency response if the phase shift at zero frequency were not zero or some multiple of π. It is only of academic interest except in a system where the carrier itself must carry information (such as synchronization) in addition to being modulated.

PHASE DELAY—The delay encountered by a single unmodulated frequency in passing through a network or channel. Phase delay (in seconds) is $\frac{\textit{phase shift}}{\textit{frequency}}$, or $\frac{\phi}{\omega}$ where ϕ is phase shift in radians and ω is frequency in radians per second. Phase delay is usually of interest only in special cases such as where a steady-state tone or frequency is used to transmit information, such as for timing or synchronization, or where individual cycles of the carrier are used for some purpose.

PHASE DISTORTION—This has the same meanings as *envelope delay distortion.* The term refers to the fact that distortion of the signal occurs because phase shift in the channel is not directly proportional to frequency. If phase shift is linear or directly proportional to frequency, all frequencies are delayed an equal amount and there is no distortion. Only in such a distortion-free channel is *phase delay* equal to *envelope delay.*

PHASE-FREQUENCY DISTORTION—See *phase distortion* and *envelope delay distortion.*

RELATIVE DELAY—The difference between the maximum and minimum delays occuring in a channel or band of frequencies. In Figure 2, the *relative delay* of the channel is t_1-t_2. It is this variation of delay in a channel that causes *delay distortion.* Most phase (or delay) equalizers reduce *relative delay* by adding delay at those frequencies where *absolute delay* is at a minimum. Such an equalizer increases *absolute delay* in order to reduce *relative delay.* ●

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can be calculated by differentiating phase shift with respect to frequency:

$$\text{delay}\,(t) = \frac{d\phi}{d\omega}.$$

Since virtually all forms of electrical communication employ signals which require a band of frequencies for successful transmission, envelope delay is the form of delay of greatest general importance. In this article, further references to "delay" will mean *envelope* delay unless otherwise indicated.

Usually, only *relative* delay — the maximum range or difference in delay values in a channel — is of importance, since only the delay *difference* causes distortion in the received signal. Absolute delay — the *total* delay experienced by signal elements — is usually not important except where signals or parts of a signal are transmitted from one point to another over different routes and must arrive at the same time.

Delay Equalizers

Where amplitude response of a circuit is unsatisfactory, an equalizer is used to introduce a controlled amount of loss at certain frequencies in order to obtain the desired performance. In the case of excessive relative delay, a network which would correct the phase shift characteristics of the communications channel might very well neutralize the desired attenuation of the filters responsible for the delay. Special phase equalizers are required to overcome this problem. Ideally, a phase equalizer is a network which introduces a controlled amount of phase shift at various frequencies, but causes no signal loss at all. Practical phase equalizers, however, cannot avoid affecting amplitude response to some degree.

Although it is possible to design filters which will reduce or postpone the appearance of delay distortion (by adding special kinds of filter sections), the more common practice is to add a so-called "all-pass" network which adds delay at selected frequencies, but

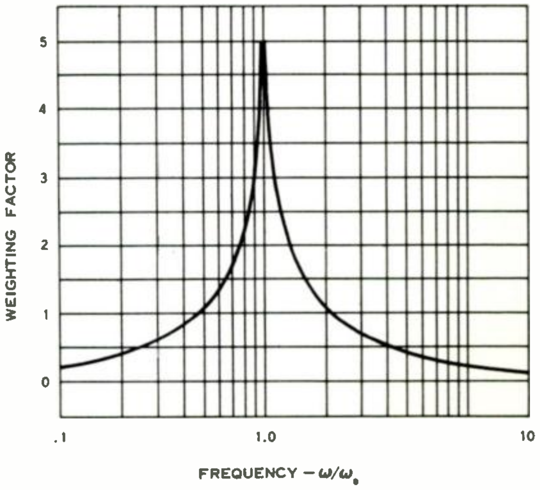

Figure 4. Weighting factor for the phase shift near the resonant or cutoff frequency of a network or line. Phase shift is very high at resonance, but falls off rapidly at higher or lower frequencies.

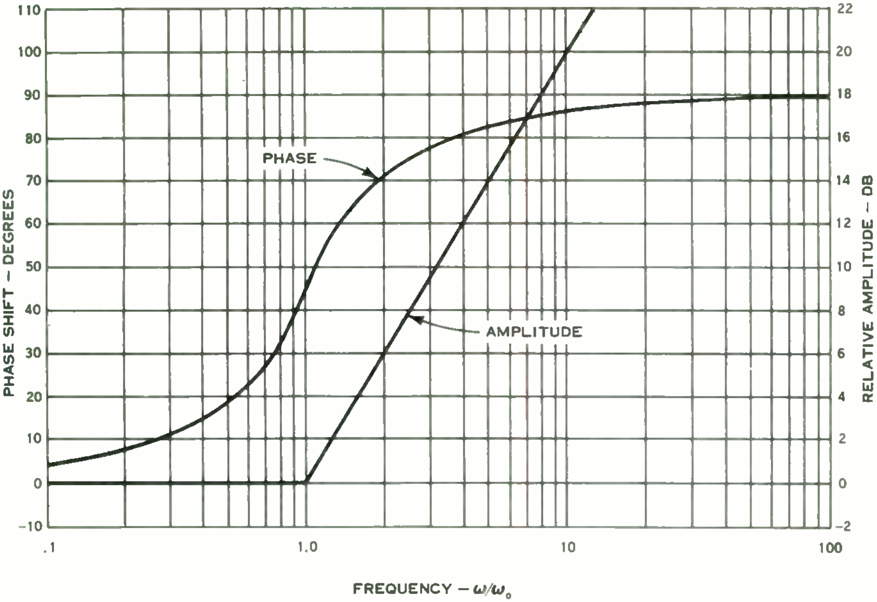

Figure 5. Fictitious amplitude characteristic of a network and the actual phase shift that would result. The smooth phase shift curve shows the weighting effect diagrammed in Figure 4.

which adds negligible attenuation at any frequency.

In a carrier system, the channel bandpass filters which isolate individual channels from each other are the principal sources of delay distortion. These filters should have uniform amplitude response within a desired band of frequencies, but must exhibit a very rapid attenuation of all frequencies outside the desired band. Unfortunately, such rapid change in the attenuation characteristic of a filter is also accompanied by rapid changes in the phase shift, as indicated in Figure 5. As a rule, phase shift is maximum at the cutoff frequency or resonant point of a circuit, but declining at other frequencies, as shown in the weighting curve, Figure 4. Thus, a circuit having linear attenuation characteristics would still have non-linear phase shift and would introduce envelope delay.

Figure 6 shows a typical all-pass network and some of the delay characteristics that may be obtained with such a network. The different delay characteristics are obtained by changing the values of components. Since the network impedance and the frequency at which the delay is obtained are also affected by component values, design of such equalizers is a complex art.

A typical equalizer will have several sections, each of which may have a different cutoff frequency (f_c) and a different "width factor" (b). Such equalizers are usually custom-designed to correct the delay characteristics of a certain type of equipment or communications path. Figure 7 compares the envelope delay characteristics of a carrier system channel without equalization, the *amplitude* response of an experimental 3-section equalizer, and the delay characteristics of the equalized channel. Note that there are three "humps" or ripples in the curve representing the equalized delay characteristics — one for each section in the equalizer.

The more sections that are used in a phase equalizer, the finer the ripple in the delay characteristic. These ripples result from the inability to design an equalizer which perfectly neutralizes the delay. The remaining delay causes distortion in the form of echoes. Where the ripples are coarse, as when few equalizer sections are used, the echoes are separated very little from the signal and may have only the effect of changing the amplitude of the signal. Where the ripples are fine, the echoes are delayed more. It has been shown that a system is considerably less tolerant of noise interference as the time separation between signal pulse and echo is increased. Thus, the fewer equalizer sections required to achieve a given relative delay tolerance, the less susceptible the system is to interference. This sensitivity does not increase, however, after the echo is delayed more than one pulse-width for data, or about 60 picture elements in the case of facsimile.

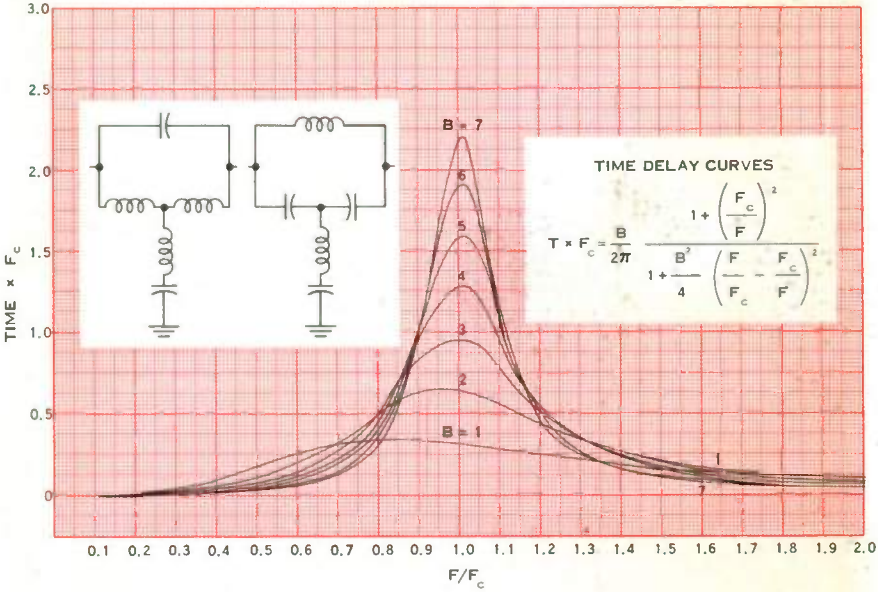

Figure 6. Two typical all-pass network configurations and a family of envelope delay curves which may be produced with such networks. Width factor (b) and critical frequency (f_c) are controlled by the values of the network components. Typical delay equalizer will consist of several sections, each designed to add a carefully-determined amount of delay to a small portion of channel passband.

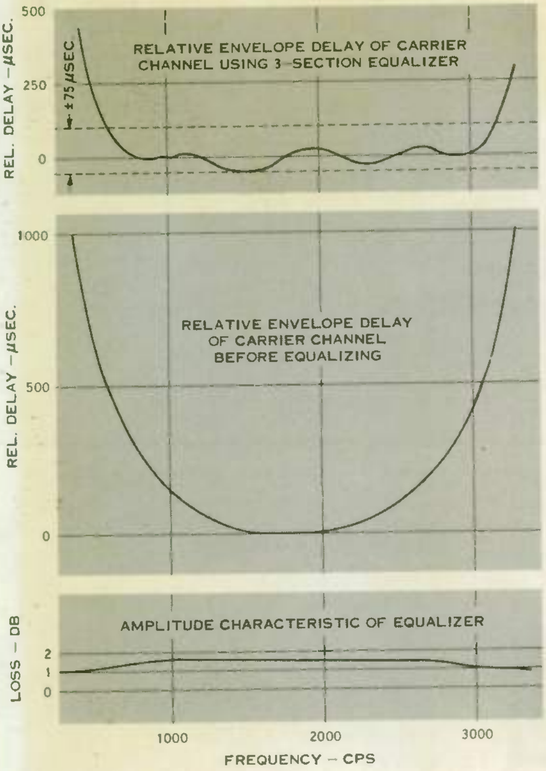

Figure 7. Center panel above shows the envelope delay characteristic of a typical carrier system voice channel before equalizing. Addition of a 3-section equalizer reduces relative envelope delay to ±75 microseconds over a large portion of the bandwidth, as shown in top panel. Bottom panel shows that amplitude response of the equalizer varies less than 1 db despite effect on envelope delay.

Future Needs

The long-range trend in the communications industry is toward more and more pulse transmission, both for data and for speech. It is primarily pulse transmission that is vulnerable to delay distortion. In modern systems, a message may be transmitted from one point to another over one of several possible routes which may differ greatly from one another in their phase response. In order to obtain best use of the existing communications networks, it will be necessary to obtain uniform delay characteristics, regardless of the routes. Perhaps it will be possible to devise techniques for automatically equalizing the phase response of an entire circuit after a connection has been obtained, regardless of circuit length or the nature of the means of transmission. ●

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