The Lenkurt Demodulator

NEWS FROM LENKURT ELECTRIC

VOL. 12, NO.1 JANUARY, 1963

The Transmission of PCM over Cable

For reasons outlined in a recent issue (November, 1962), new multiplexing systems which use time division and pulse code modulation are now beginning to appear in commercial service. Initially, at least, these new systems are restricted to the relatively short trunks between telephone exchanges. The relative immunity of PCM to interference enables it to use bandwidth in exchange cable that cannot be used by conventional carrier systems. It isn't easy, however; the problems of transmitting multichannel PCM signals over cable are formidable — and not yet perfectly solved. This article reviews the more basic problems and some current approaches to solving them.

Three major problems must be overcome by time-multiplexed PCM systems. The conflict between available bandwidth and transmission quality must be resolved. The effects of crosstalk between two or more systems sharing a cable must be minimized. Most important, each of the pulses which comprise the signal—more than 1.5 million per second—must be restored and held to extremely close timing standards, in the face of distortion and interference which tend to introduce uncertainty as to the presence of a pulse or the exact instant when it should most easily be detected.

A conflict between transmission quality and available bandwidth stems from the basic nature of PCM. The PCM signal consists of a stream of code pulses which *represent* samples of the original waveform, and from which the waveform can be reconstructed. These pulses are much easier to squeeze through an unwilling and noisy transmission medium than the analog signal which they represent.

Inevitably, however, the reconstructed signal can be only an approximation of the original waveform, since only a limited number of amplitude "steps" can be represented by the code groups. The differences between the original message waveform and the code-derived facsimile show up as "quantizing" noise. Assuming that all pulses are accurately regenerated in transmission, the noise acquired by the pulse train in transmission is essentially eliminated in the regeneration process. So long as the PCM remains above threshold, so that the pulse codes can be identified accurately, transmission quality remains uniform. This is in contrast to the performance of conventional methods, where transmission quality varies with signal level, as shown in Figure 1.

The use of additional digits in the code improves signal quality and reduces quantizing noise, but this also increases the bandwidth required for transmission. Bandwidth is directly proportional to the number of digits in the pulse code. This bandwidth requirement places a practical limit on the number of digits that may be used in PCM transmission. This is particularly true when multi-channel PCM signals are transmitted over exchange trunk cables, since these have a very high rate of attenuation at the required frequencies. If signal quality is improved by the use of additional code digits, it reduces the number of channels that may be accommodated or makes necessary more frequent or more expensive regenerative repeaters.

Instantaneous Companding

One way of reducing the total quantizing noise present in a PCM transmission without increasing the number of code digits is to vary the size of the quantizing steps to take advantage of the nature of speech. Statistically, low speech amplitudes (that is, the softer sounds) are much more probable than the very great amplitudes. Figure 2 shows a typical distribution of speech signal voltages relative to the rms or effective level. Note that there is only a 15% probability that the voltage will exceed the rms value, and that fully 50% of the time speech voltage will be less than one-fourth the rms value. Where uniform quantizing is used, many of the quantizing steps are "wasted" and others are "overworked." By altering the quantizing characteristic to favor the weak signals at the expense of the very high amplitudes, more of the speech energy is subjected to relatively "fine-grained" quantizing, thus lowering the total amount of noise. Of course, high signal amplitudes (which are relatively rare) will suffer more degradation than with uniform quantizing.

This technique, called *instantaneous companding,* can be achieved in either of two principal ways: compress the amplitude range of waveform samples before they are quantized, then use a

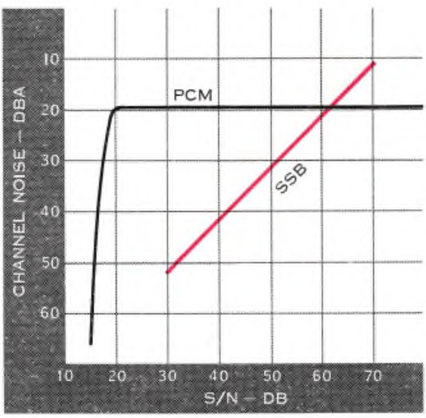

Figure 1. Arbitrary comparison of signal quality versus transmission S/N ratio. SSB signal quality improves in direct proportion to increase in signal power. PCM signal quality is based on quantizing noise caused by coding. Relative positions of the two curves may vary widely, since different factors control each. PCM threshold is largely determined by intersymbol interference, timing accuracy, and differential delay. SSB signal quality is controlled by the absolute value of line noise.

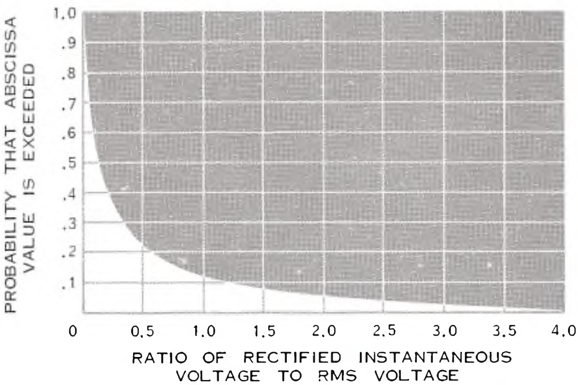

Figure 2. Statistical distribution of single-talker speech amplitudes relative to nominal rms amplitude value. Very low speech volumes predominate, and high amplitude values are relatively rare.

linear quantizer (one with steps of equal size), or vary the sizes of the quantizing steps themselves, so that the steps are smaller and more numerous for low amplitudes. With either method, it is necessary to reverse the process at the receiver in order to restore the original range of amplitude values.

Instantaneous companding produces a significant improvement in signal quality. So long as the compressor and expandor complement each other, a wide range of compression-expansion characteristics may be used. The optimum characteristic depends on the nature of the talkers, instrument weighting and similar factors. Using a certain typical compression-expansion characteristic that varies logarithmically with signal amplitude, an improvement of better than 26 db in the signal-to-quantizing noise ratio is obtained. This is the equivalent of about four additional digits in the pulse code. In systems which use a seven-digit code, instantaneous companding provides quality equivalent to an eleven-digit code.

Regardless of the method by which instantaneous companding is achieved, it is extremely important to match the expansion and compression curves of transmitters and receivers quite precisely. Since compression is a form of "pre-distortion," it is vital that the expandor "track" the compressor as closely as possible in order to cancel out the deliberately introduced signal distortion. Mistracking will cause changes in the transmission net loss as signal level changes, and will restore some of the noise that companding seeks to suppress.

Tracking error between compressor and expandor is sufficiently important that great care must be taken to stabilize the drift of diodes or other non-linear components used to achieve the compression and expansion characteristics. Such techniques as temperature control may be required, adding considerably to the cost and complexity of PCM terminals.

One solution to this problem is provided by a *non-linear coder* which, instead of using the inherent non-linearity of such components as diodes to achieve the companding characteristic, employs linear components (such as resistors) to form a network in which component values yield the desired characteristic. Even if the network components change value with age or temperature, they all tend to change together, thus avoiding alterations in the compandor characteristic curve. If maximum and minimum values on the curve are controlled, all the points between tend to remain the same.

The companding curve obtained with such a network may not quite achieve the full quantizing noise improvement possible if the speech amplitude distribution is exactly matched, since the network only approximates the desired companding characteristic — which, itself, is only an approximation—with a series of short chords, rather than with a continuously smooth curve. However, quantizing error noise is still reduced on the order of 25 db, and terminal equipment can be more reliable and less costly.

The Timing Problem

Rigorous control of the timing of the transmitted pulses is obviously necessary in a multiplex system based on time separation. When the system employs PCM, timing accuracy requirements become even more stringent. High-speed pulses undergo severe attenuation and distortion when they are transmitted through cable. Energy is robbed from each pulse by attenuation and cross talk. Variations in the speed of propagation and delay of the various frequency components of the pulses spread some of each pulse's energy into the time slots occupied by other pulses. This fusing together and mutual intrusion on each other by adjacent pulses is called *intersymbol interference.* At the high frequencies necessary in a multi-channel PCM system, attenuation becomes very high. Crosstalk coupling into adjacent pairs increases with frequency. At the 1.5 megabits-per-second pulse rate, coupling loss between pairs in the same cable may, in some cases, be less than the transmission loss in the pairs themselves. Accordingly, a severe near-end crosstalk problem may exist when two or more systems share a cable.

The ability of PCM to overcome crosstalk and other interference is based on the ability to recognize the presence or absence of the code pulses with great accuracy. Transmission errors result in clicks and snaps, since a false amplitude —one that has little or no relation to the correct signal waveform being reconstructed—is produced by the decoder. Such transmission errors become increasingly likely as the pulse rate increases. The transmission limitations

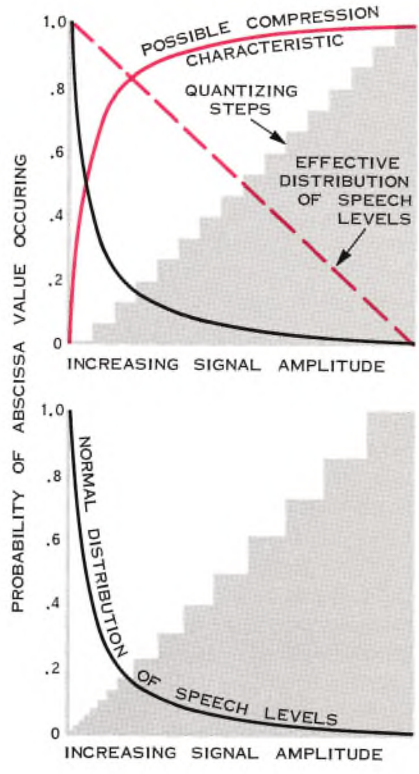

Figure 3. Linear quantizing, shown in A, uses relatively few quantizing steps for a majority of speech amplitudes. By using a compression characteristic (solid red curve) which amplifies the plentiful low amplitudes more than the high values, more uniform quantizing is obtained. As shown in B, this increases the number of quantizing steps for low amplitudes, results in less quantizing noise.

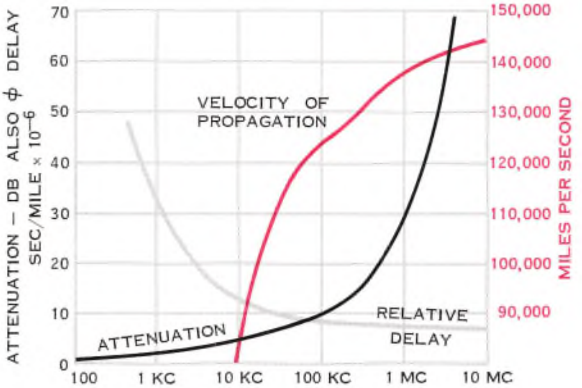

Figure 4. Measured values of attenuation, velocity of propagation, and relative delay of various signal frequencies in typical 22 gauge exchange cable.

of the cable, diagrammed in Figure 4, result in large amounts of intersymbol interference, with the result that pulses become harder and harder to identify. Under these conditions, noise and crosstalk have a greater effect in increasing transmission errors.

In order to regenerate and re-time pulses accurately despite the effects of severe intersymbol interference, it is necessary to sample the pulse train periodically, at just the instant that a pulse, if present, would achieve its peak value. This requires very accurate timing.

In addition to masking the signal pulses, crosstalk or other interference tends to shift the position of individual pulses, creating "timing jitter" which adds to the uncertainty about the presence of pulses. In order to avoid an accumulation of timing error from repeater to repeater (which would sharply restrict system length), each repeater must regenerate pulses which have the correct duration and spacing. This also requires that precise timing information be available at each repeater. There are a number of ways that this can be done. One is to use extremely accurate and stable oscillators at each repeater. This would be successful only if the oscillators did not deviate more than about 30° in phase from the incoming signal. Although this is attainable, it is expensive.

Another approach might be to transmit a pilot tone. This presents the difficulty of providing a very high quality channel for the pilot so that noise of various sorts would not introduce jitter or very short term variations in the regularity of the pilot signal itself. The need for this type of auxiliary channel defeats the purpose of PCM transmission, since one of the objectives is to reduce the vulnerability to interference and to eliminate the need for relatively "delicate" transmission methods. Since the pilot would require complete freedom from crosstalk, it would almost certainly have to be sent over a separate but parallel transmission path, possibly another cable.

An accepted solution is to derive the timing information from the data stream itself. Since the signal consists of a series of periodically recurring pulses, these can be used as a reference for controlling an oscillator, or for exciting a resonant circuit to produce a timing wave. In both cases, reasonably high oscillator stability or resonant circuit Q is desired, but not so high that the resulting timing wave is too "stiff" to be corrected by the incoming pulse stream. Above all, economic considerations demand that the simplest method that will provide satisfactory timing be used, since practical PCM repeaters are still, at present, more complex and expensive than repeaters for conventional exchange trunk carrier systems. For this reason, contemporary systems use a simple resonant circuit tuned to the pulse repetition frequency. The sine wave obtained from this circuit is amplified and used to derive a narrow sampling pulse. Inevitably, economically realizable circuits fall short of ideal performance, so a small amount of timing jitter is unavoidable, and this shows up in small perturbations of the reconstructed pulse train. Since these irregularities must affect pulse retiming at the next repeater, timing error accumulates and eventually limits the overall length of the system. If a precision "clock" or timing generator is included at intervals, this source of error can be greatly reduced.

Transmission Techniques

The very rapid increase in cable attenuation as frequency becomes higher

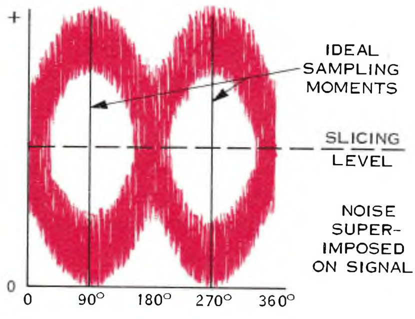

Figure 5. Shaped pulses assume sine-wave form. Noise superimposed on the waveform tends to obscure actual signal value. Timing errors can result in non-optimum sampling, increase vulnerability to crosstalk and noise.

poses several serious problems. Part of the loss is due to crosstalk coupling into adjacent pairs in the cable. Not only is transmission loss great at the 1.5 mc pulse repetition frequency, but crosstalk is formidable. There are several ways of coping with these difficulties to obtain better transmission. One is to "shape" the transmitted pulses so that they have the minimum bandwidth consistent with their repetition rate. Another is to "encode" the signal into a form that shifts the energy spectrum of the pulse train so that more of it is concentrated at lower frequencies. The binary pulses from the transmitter or the pulse regenerator are shaped by passing them through a filter that selectively attenuates some of the very high-frequency harmonics that are inherent in square-wave pulses. The pulses can be shaped at very low level, then amplified for transmission. The filter characteristic is chosen to assure minimum attenuation in the transmission medium. Since less of the transmitted energy is absorbed or coupled into adjacent pairs, (due to a lowering of the extraneous high frequency components), crosstalk is reduced, and there is greater likelihood of the pulse retaining its identity. This technique is not new, having been used in telegraphy for decades, but it assumes much greater importance at the very high pulse repetition rates used in PCM.

Although it is convenient and conventional to diagram a pulse train as consisting of a series of unipolar pulses such as would be obtained by making and breaking a circuit through which a direct current flowed, there are objections to unipolar pulses in practical PCM systems. It becomes necessary to use dc amplifiers instead of the much less expensive ac amplifiers, and transformers cannot be used for signal coupling at the terminals and repeaters. Furthermore, a train of unipolar pulses

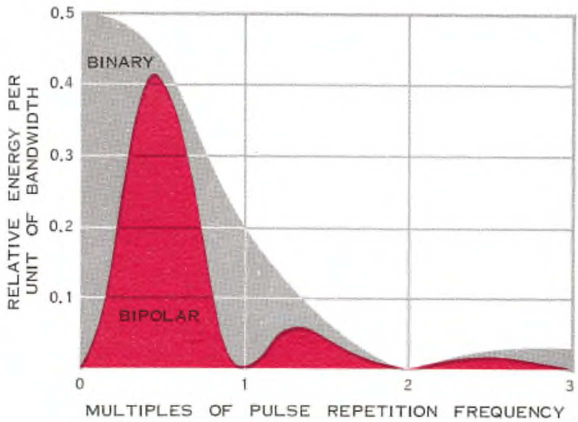

Figure 6. Energy distribution of binary and bipolar signals for 50% duty cycle pulses. Binary signal has strong discrete component at the pulse repetition frequency. Bipolar signal has no frequency components at dc or at the pulse repetition frequency; most energy falls near half the pulse rate frequency.

requires more bandwidth than other signals which have the same information capacity.

These objections are overcome by using a "pseudo-ternary" or bipolar type of signal. These are signals in which consecutive marks are of opposite polarity, and space is represented by zero voltage or neutral. This type of transmission has the additional advantage of requiring only 1/4 the power-handling capacity for a given overall voltage range. As shown in Figure 6, most of the energy of bipolar signals is concentrated near frequencies of about half the pulse frequency. Accordingly, there is much less energy coupled into other cable pairs because of the reduced line loss and crosstalk coupling. By forcing the signal to alternate between positive and negative values, the need to transmit direct current is eliminated and transformer coupling becomes permissible. Although there is no energy component at the actual pulse rate with bipolar signals, it is easy to obtain the required 1.5 mc clock signal with a simple full-wave rectifier or frequency doubler. Since a bipolar signal may assume any of three levels, it is somewhat more vulnerable to interference than a true binary signal of the same amplitude. However, this can be overcome by either increasing the signal amplitude, increasing the stability of the timing signal at each repeater, or by shortening the span between repeaters.

An even more promising method of processing PCM signals for transmission has recently been invented at Lenkurt. This technique, known as Duobinary Coding, doubles the number of pulses that may be transmitted through a given channel, compared to bipolar or binary signals. This technique will be described in the February, 1963 issue of the DEMODULATOR. •

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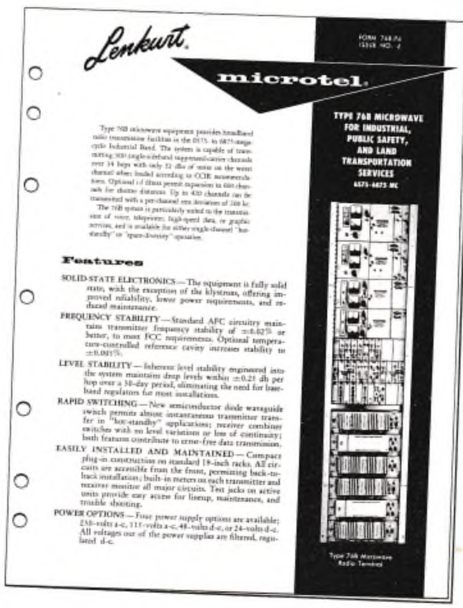

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