The Lenkurt® Demodulator

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TIME-DIVISION MULTIPLEX—

New Promise for Old Technique?

Time-division multiplex, oldest and simplest method of deriving additional communications channels from a transmission medium, has never been really practicable before now. Frequency-division multiplex, or "carrier," although more complex, was originally easier to achieve than time-division because the particular techniques required were further developed than those required for time-division multiplex. Progress in semiconductor technology and computer techniques has now largely removed this disparity in knowledge so that time-division systems may now be economically feasible in certain applications. This is the first of several articles which discuss the characteristics of such systems.

Conventional frequency-division multiplex techniques have developed from our ability to produce electrical filters which can separate and, in a sense, create *bands* of frequencies. By using each frequency band as a separate channel for transmitting information, it is possible to transmit many individual channels simultaneously over a single transmission medium. The bandwidth required is the sum of the individual channel bandwidths, plus a small amount between channels.

Much the same result is obtained with time-division systems. Many individual channels share the transmission medium by "taking turns," each being connected to the line very briefly, then replaced by the next. This is repeated again and again so swiftly that there is no loss of message intelligence in any of the channels. If the time during which each channel is connected to the line is kept very short, many channels can share the transmission facility.

At the receiver, the same process occurs in reverse. Some kind of signal distributor or commutator arrangement is required to "sort" the samples as they arrive in sequence, and distribute them to the appropriate lines at the

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proper instants. This requires precise synchronism between transmitter and receiver. If synchronism fails, all channels are garbled and lost. Significantly, it was the lack of ability to maintain synchronization that prevented the general adoption of time-division multiplexing during the last century, shortly after the invention of telegraphy, and later, telephony. This left the field open for the frequency-division techniques which have become nearly universal.

By now, most technical obstacles to time-division multiplexing have been overcome. The development of cheap but efficient solid-state devices such as transistors, plus highly refined electronic switching techniques, has eliminated the relative economic disadvantages that time-division previously suffered. These, plus certain other advances have stimulated new interest in time-division multiplexing for communications systems.

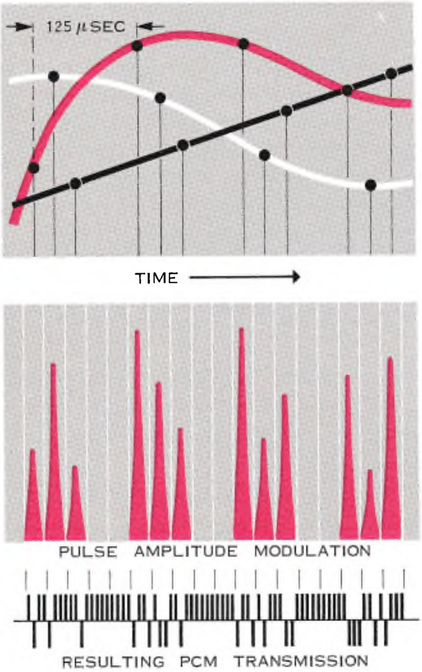

Figure 1. Two samples per cycle of highest frequency adequately define each channel. If samples are brief, many channels can share the common line.

The Role of PCM

An important factor behind the growing interest in time-division multiplex is its natural suitability for use with electronic time-division switching and pulse code modulation (PCM). Electronic switching is based on the same digital techniques used in modern electronic computers. PCM is also a digital system, able to transmit any sort of signal—even television—in the form of coded binary pulses. This at once yields several advantages. Unlike conventional analog transmission methods (in which a current or carrier wave is varied in a manner analogous to the original message), the message is sampled periodically and the values observed are *represented* by a coded arrangement of several pulses. Each separate signal value has a unique arrangement of pulses. Thus, only the presence or absence of pulses — not their shape —determine the received message and its quality.

This is very similar to conventional teletypewriter communication, in which the transmitted characters are represented by various combinations of a five-pulse code. Regardless of how badly the code pulses may be distorted or degraded in transmission, the sharpness or clarity of the *characters* reproduced at the receiving printer are obviously not changed or altered in any way. Distortion of the transmitted pulses merely increases the chances of a mistake in interpreting the code and the printing of a wrong character.

In addition to providing improved transmission, the combination of these digital techniques can result in substantial economies. By integrating the equipment used for switching and multiplexing, equipment cost may be much lower than if the two techniques were used separately.

It should be pointed out that there are many types of pulse modulation. Almost without exception, however, PCM or related approaches (which we will class as "PCM" in this issue) are the only ones now seriously considered for time-division multiplexing systems. This stems from the great efficiency of PCM in overcoming interference and noise. Even more important, PCM permits the use of regenerative repeaters.

Regenerative repeaters detect the presence or absence of "old," distorted pulses and replace them with perfect new ones. The regenerative repeaters must be spaced closely enough to correctly identify the incoming distorted pulses, and be able to send out new pulses which precisely match the original pulse stream. When done perfectly, it is theoretically possible to transmit messages for unlimited distances without degradation. This would allow uniformly high transmission quality regardless of distance; a call across a continent would be as clear and distinct as a call next door. In practice, small timing errors tend to add up as the number of repeaters increases, eventually placing a limit on system length.

Because of the very close association between time-division multiplexing and PCM in system planning, and because many of the problems of such systems stem from the PCM, subsequent references in this article may be only to "PCM." It should be understood that time-division multiplexing is assumed, even though not always stated.

Bandwidth versus Noise

Pulse code modulation requires more bandwidth than amplitude modulation, but it uses this bandwidth far more efficiently in overcoming noise and interference than almost any other modulation method. For instance, frequency modulation (FM) also trades bandwidth for noise improvement, but rather slowly. With FM, the signal-to-noise ratio improvement (in db) is proportional only to the *logarithm* of the increase in bandwidth. Thus, to improve the signal-to-noise ratio by 10 db requires bandwidth ten times the original. By contrast, the PCM improvement in db is in *direct* proportion to the increase in bandwidth; a PCM signal requiring ten times the bandwidth of the original signal will yield a signal-to-noise ratio of 70 db. Note: this signal quality is inherent in the transmitted signal and is not the result of noise encountered in transmission, so long as the signal remains above the noise threshold of the system.

In order to reconstruct the original wave, at least two amplitude samples must be transmitted for every cycle of the highest frequency in the original waveform. Therefore, good reproduction of 4000-cycle telephone channels requires that 8000 samples per second be transmitted. A continuous waveform has an infinite number of discrete amplitude values. In order to represent the waveform by groups of pulses, it is necessary to limit the number of points which represent the wave to a convenient number which can be handled by the code. This is called "quantizing" the wave and is a form of approximation. The random differences between the actual waveform and the quantized approximation results in "quantizing noise" being introduced into the transmission. With error-free transmission, this is the only source of noise in the system, and yields the signal quality defined above. Quantizing noise may be minimized by using as many steps as possible, since this reduces the difference between the original signal and its coded approximation (see Figure 3).

This, however, increases the number of code pulses which must be transmitted. The number of steps is determined by the number of binary pulses or digits in each code group: number of steps $= 2^n$, where n is the number of digits in the code. Thus a five-digit code yields 32 amplitude steps, while a seven-digit code provides 128 steps. The latter reduces the quantizing error considerably. The bandwidth required is directly proportional to the number of digits; a seven-digit code requires seven times as much bandwidth as a binary (single-digit) code, but improves the signal-to-noise ratio 36 db. (The signal-to-quantizing noise ratio in db can be calculated from the expression $S/N = 10.8 + 6n$).

In view of the requirement for so much greater bandwidth than amplitude-modulated or single-sideband systems, one might conclude that PCM is totally unsuited for practical communications system inasmuch as transmission bandwidth is very costly. In many applications this is true. However, several studies have shown that the noise advantage of PCM can, under some circumstances, be used to "buy back" frequency spectrum. For instance, it might be possible to overlap PCM transmissions in frequency. Although this would be expected to result in a certain amount of interference, the systems could exhibit a very high tolerance to their mutual interference, depending on the amount of overlap.

New sources of bandwidth are being made available by various technological advances. Rapid progress in the development of lasers (optical masers) confirms the high hopes and optimistic predictions about the possibility of using light as a wide-band communications medium (see DEMODULATOR, June, 1961). Of more immediate importance, a certain propagation mode in circular waveguide actually reverses the normal loss characteristics of waveguide, resulting in *less loss as frequency increases.* This also could make almost unlimited bandwidth available for techniques such as PCM which require great bandwidth. Not all of the practical difficulties in using this type of transmission have been overcome, however. Bends, junctions, and imperfections in the waveguide have a tendency to cause the energy to be transformed from the desired low-loss mode to other modes, any of which cause increasing loss at higher frequencies.

The Practical Situation

Assuming that transmission difficulties can be overcome, is the introduction of a new approach worthwhile? In the United States alone, nearly $50 billion is invested in communications, and a similar investment exists elsewhere. Only very substantial benefits could justify radical, large-scale changes in the basic system.

The desired objective is to achieve a nation-wide or even global communications network in which any telephone or station can instantly dial any other; transmission quality would be uniformly excellent, and the influence of distance would seem to vanish. Since the network would employ digital pulses for most transmission, data could be accommodated as easily as speech. None of these objectives are completely realizable or economically practicable with the conventional tech-

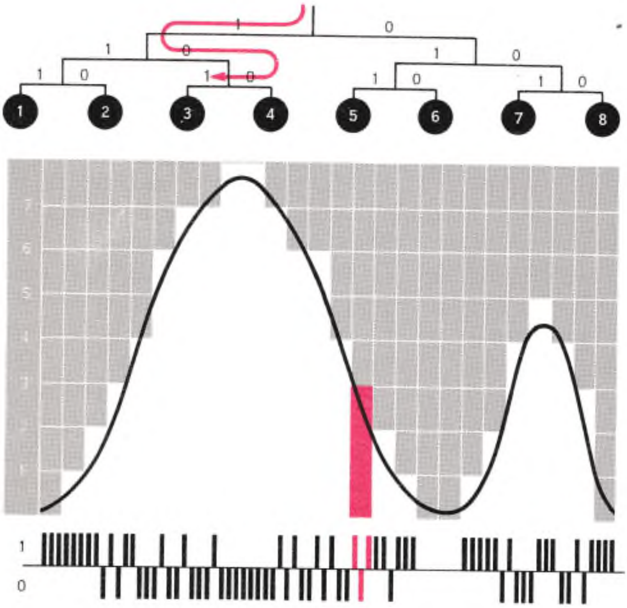

Figure 2. How a waveform can be quantized and converted into code pulses. Bandwidth restrictions limit the number of digits per sample, thus establishing maximum number of quantizing levels.

niques presently in use. However, it remains to be proved whether PCM transmission systems can successfully eliminate some of the technical and economic difficulties of present methods.

Even if a radical change is found to be desirable, it obviously cannot be accomplished overnight. Improvements have historically been evolutionary rather than revolutionary in the communications industry. New techniques have had to be compatible with the old, and this continues to apply.

There is no question but that adequate techniques for very limited PCM systems are now available. More than four years ago a laboratory model of a system which integrated time-division multiplexing, PCM, and electronic switching was successfully demonstrated. However, except for a narrow range of applications, a great gulf exists between laboratory devices and practical equipment suitable for field use.

Satisfactory PCM requires that all the code pulses be regenerated with great precision as often as required to suppress noise and distortion. The problem may be quite difficult when transmission is over facilities such as wire and cable which are severely restricted in bandwidth and which introduce large amounts of noise and cross-talk. Not only must the pulses be accurately identified and regenerated, but they must preserve their original timing exactly, since only by their exact timing can the individual channels be located and recovered. The problem of pulse regeneration and re-timing is so important that it determines the major limit on the length and performance of the new semi-experimental systems now being tried.

PCM Economics

The real benefits of PCM appear to be realizable only in very large networks spanning great distances. This poses a problem, since it isn't desirable or practicable to innovate on such a scale, particularly with techniques which are still only a little beyond the experimental stage. Accordingly, it is necessary to find some other application in which PCM can be introduced and in which practical experience can be obtained for perfecting and refining the equipment.

At this time, PCM seems to be most suitable for linking relatively close terminals linked by wire or cable. In modern telephone plant, this is fulfilled best by relatively short trunks between exchanges. Transmission by radio could reduce the need for frequent regenerative repeaters. However, relatively few channels could be accommodated due to the great bandwidth required compared to conventional methods. This would also result in very high cost per channel, since suitable radio equipment costs the same whether it is used to transmit a few channels or many. The same economic philosophy applies to other transmission media such as cable or open wire. Where multiplexing methods that use less bandwidth can be used economically, they will be preferred, since more channels can be accommodated in a given bandwidth. This eliminates almost all present toll circuits and tends to restrict PCM to competing with those transmission methods which are even more wasteful of capacity—notably voice frequency circuits. Thus, the principal area of application—today at least—is in linking centers which are so close together that cable pairs have been cheaper than carrier channels.

If enough channels are involved, PCM *terminals* are inherently very inexpensive. Very little equipment is re-

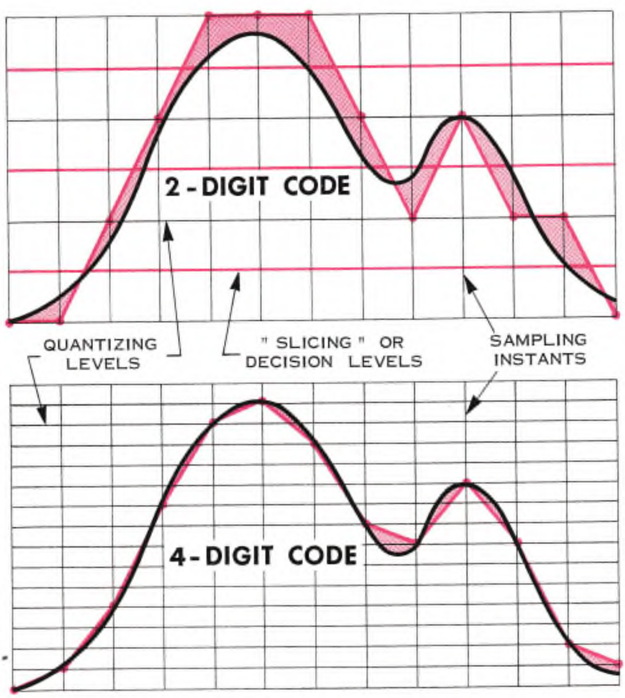

Figure 3. Signal quality is determined by how closely the quantized signal approximates original signal, a function of the number of code digits. Differences show up as quantizing noise. Each additional digit improves signal-to-quantizing noise by six db. With ideal regeneration and retiming, this quality is maintained regardless of number of repeaters or system length.

Figure 4. Pulses undergo constant attenuation and degradation in cable. Most crucial function in system is the accurate retiming and regeneration of distorted pulses.

quired by individual channels and all share the common equipment, which primarily consists of switching and encoding circuits. The number of channels transmitted is limited only by the ability of repeaters to identify and restore pulses, and this is controlled by the pulse rate and the transmission characteristics.

Most present systems use a seven-digit code, with an eighth digit for signaling. Since each channel should be sampled 8000 times per second, 64,000 pulses per second are required for each channel. The greater the number of channels which must share the transmission medium, the higher the pulse rate that is required. In order to transmit 24 channels by this means, more than 1.5 million pulses per second must be transmitted.

Obviously, this imposes a severe transmission requirement on ordinary exchange cable pairs, which are normally considered to be rather limited in bandwidth. This is a secondary consideration with PCM, however, since bandwidth limitations only determine the degree of distortion suffered by pulses as they travel over the line. The higher the pulse rate, the more the pulses are degraded in transit, and the harder they become to identify after traveling over the line. The practical significance is that regenerative repeaters merely have to be closer together along the cable. If fewer channels are transmitted, or if better cable is used, repeaters could be more widely spaced, other factors being equal. Since existing cable must be used in the majority of cases, it is desirable to design the system for repeater spacing which matches that of existing loading coils—usually about a mile. Although loading coils improve the line characteristics for speech transmission, they drastically impair pulse transmission, particularly at high speeds. By matching repeater and loading coil spacing; it becomes particularly convenient to remove the coils and substitute repeaters.

If existing exchange cable characteristics largely determine repeater spacing, repeater quality strongly influences the number of channels which may be accommodated, and the over-all economics of the system. An important conflict exists between the cost and capability of repeaters. Since repeaters are required every mile they should be relatively inexpensive in order to be competitive. The stringent requirements for timing accuracy are easily met only with relatively complex or refined techniques, which tend to be expensive.

This, and such other technical problems as crosstalk considerations and the reduction of quantizing noise in PCM systems will be discussed in the next article in this series. It will appear in the January, 1963 issue. •

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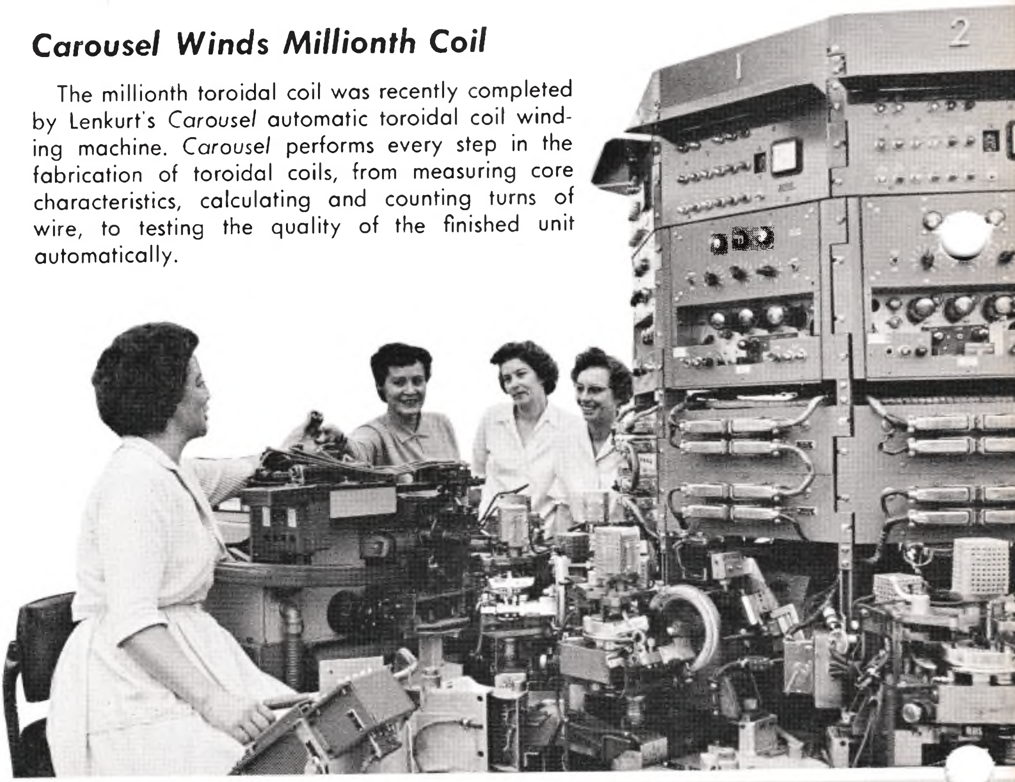

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