The Lenkurt® Demodulator

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The push for FASTER DATA TRANSMISSION

Demand for faster data transmission is growing. Development of high speed computers and other devices which handle data faster than previously possible is stimulating this demand. The growth of electronic data processing is not confined to any particular segment of our economy, but seems to be almost universal. Since different types of operation often have different data requirements, the need for fast transmission is not universal. This article discusses some of the practical and theoretical aspects of faster data transmission.

In the decade and a half since the end of World War II, a revolution has occurred in the mechanics of business operation. Computers, business machines, and electronic control processes have taken over functions that once required large numbers of clerks, typists, bookkeepers, and others. Increased use of electronics has not only speeded many management functions, reduced operating costs, and provided information that was impractical to obtain under older methods of operation, but has made possible the coordination of numerous distant operations with an efficiency never before attainable.

A big advantage of this "new look" in business technique is that distant machines may be connected together by means of a data channel so that they communicate directly with each other in their own code language, without need for human intervention or human error. Thus, the machines are free to transfer information at their own natural rate—usually thousands of times faster than humans can communicate or handle information.

For instance, in Washington, D.C., two giant computers operated by the National Bureau of Standards and the U. S. Weather Bureau have been linked by microwave so that the machines may supplement each other in handling unusually massive problems, where speed is essential. Similarly, six large com-

LOCKHEED MISSILES AND SPACE

Figure 1. Large digital computer installations such as shown here may be linked by microwave with similar installations to increase the capacity and utility of both. Such interconnection requires data transmission capabilities in the order of hundreds of thousands of bits per second.

puters used by North American Aviation and its subsidiaries in the Los Angeles area are being linked by microwave to extend their usefulness. In such systems, transmission rates of hundreds of thousands of bits per second may be attained.

Speed Limits

Are there any restraints on the speed with which data can be transmitted from place to place? The answer, of course, is "yes", since nothing is achieved without cost. Two important restraints exist: the economics of communication, and physical law, described in information theory studies.

In the very earliest days of telegraphy, experimenters quickly discovered that simple, square-shaped pulses, such as obtained by closing and opening a telegraph key, gradually distorted and "melted down" until they were lost as they travelled over increasing lengths of wire.

Lord Kelvin, one of the early researchers, found that the minimum duration of a barely distinguishable pulse was proportional to the quantity RCL^2, where R and C are the resistance and capacitance, respectively, per unit length (L) of the transmission path. Since R and C were more or less determined by cable manufacturing techniques of the day, Kelvin found that signaling speed was inversely proportional to the square of the transmission distance. In other words, if the transmission path were doubled, maximum signaling speed would be reduced to one fourth.

Thus, it became evident that each circuit had a certain minimum response time. Electrical pulses which were briefer than the minimum response time of the circuit just couldn't get through as identifiable signals.

After the invention of the telephone, the concept of *bandwidth* was recognized and linked to the response time of communications circuits. It wasn't until 1924, however, that bandwidth was completely understood. H. Nyquist, a mathematician at the Bell Telephone Laboratories, proved mathematically that the required bandwidth for a communications channel is directly proportional to signaling speed, and that the minimum bandwidth required for transmission of a signal was essentially equal to half the number of binary pulses per second.

Nyquist showed that although there was a limit to the number of pulses per second that could be transmitted over a given communications channel, each pulse might have several distinguishable states or conditions, each of which could carry information. Thus, if amplitude were the variable conveying the information, and each pulse had four possible amplitudes, twice as much information could be transmitted as in a system where pulses had only two possible values.

Nyquist showed that the limit to the number of information-carrying states was related to the noise in the circuit. Without noise, there would be no limit to the rate at which information could be transmitted. In the presence of noise, however, the difference in value between two levels or states must be at least twice the value of peak noise. Otherwise, there will be uncertainty as to the value of the pulse.

The same limitation applies to continuous waveforms as well as pulse signals. Actually, there is no real difference between the two. Although a continuous wave may contain an infinite number of points which define its shape, it does not contain an infinite number of information-carrying values. In fact, periodic samples of the waveform can be used to reconstruct or define the waveform perfectly if they are taken often enough. The waveform doesn't have to be sampled very often to make a perfect reconstruction—sampling at twice the highest useful frequency in the signal will do. Thus, if 3000 cps is the highest useful frequency in a telephone channel, a series of brief samples taken at the rate of 6000 per second will precisely and exactly duplicate the telephone conversation! The samples can be as brief as desired. In fact, the shorter the better. Thus, a series of pulses can serve in lieu of a continuous waveform, with no loss whatsoever.

Delay in Transit

One of the important technical problems of high speed data transmission is *delay distortion,* or envelope delay distortion.

Signals traveling over physical transmission paths tend to be shifted in phase by amounts which vary with their frequency. This phase shift is produced by the inductive and capacitive reactance in the system, and results in the signal being delayed or slowed down. Although electricity travels at the speed of light, the various inductances and capacitances throughout the system require a definite time to charge up and then discharge in response to signals.

Such delay is not objectionable if the phase shift is linear; that is, if it is directly proportional to the signal frequency. In this case, all of the component harmonics of the pulse are delayed an equal amount. If the phase shift is non-linear with respect to frequency, pulse components are delayed unequal amounts, resulting in delay distortion.

When a tone or carrier is keyed rapidly to produce data pulses, sidebands are produced at frequencies equal to the sum and difference frequencies of the carrier and the keying rate. The sidebands are an important part of the pulse, since they carry most of the information conveyed by the pulse. If the sidebands are shifted in amplitude or relative position, the pulse cannot be accurately reconstructed at the receiver. Figure 2 compares the effects of linear and non-linear phase shift on the delay characteristics of a communications channel.

Unfortunately, effective wave filters, such as used in telephone carrier systems, have very non-linear phase shift characteristics. Delay distortion is no problem in telephony, for the ear cannot detect phase variations. Thus, it hasn't been necessary to correct for delay distortion in telephone systems. In telegraphy, and particularly in high speed data transmission, the problem becomes very serious, and becomes more troublesome as transmission rate increases. At higher speeds, the keying rate goes up and the sidebands are more widely spread in frequency from the carrier. The maximum pulse duration must necessarily go down to accommodate the higher pulse rate. Because of the shorter pulse duration, slight shifts in time or phase have a greater effect in degrading the pulse and losing it. The extra frequency range of the sidebands moves them to frequencies where delay is greater, thus reducing the chances of the pulse being reconstructed accurately at the receiver.

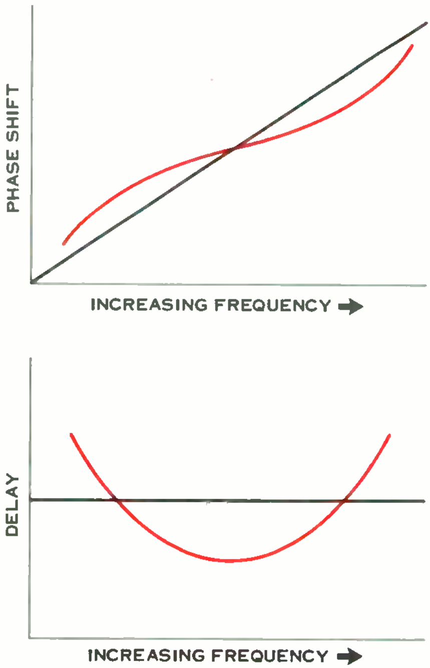

Figure 2. Comparison of the effects of linear and non-linear phase shift on envelope delay in a communications link. Linear phase shift produces uniform delay at all frequencies. Non-linear phase shift causes delay to vary with frequency.

Ideally, all components of a pulse should be delayed equal amounts. Normally, the difference in the delay imposed on different components of a pulse should not exceed five to ten percent of the pulse duration. This is a requirement of practical systems, and allows a certain amount of margin or protection against other forms of distortion that may occur, such as bias distortion, fortuitous distortion, and the like. Additional delay up to nearly 50% may be tolerated in circuits where interference and other adverse influences are very low or absent.

Equalizing Delay

The adverse effects of delay distortion can be reduced by adding delay to selected portions of the transmission band so that delay *differences* are minimized across the band required for transmitting the data pulses. This is done by using filter-like reactive elements that have greater delay-producing characteristics than amplitude-attenuating effects. When applied to the circuit requiring correction, delay characteristics are changed without significantly affecting the selectivity of the filters responsible for the delay distortion. Figure 3 shows the delay and amplitude characteristics of a multi-link carrier channel before and after delay compensation. In this particular case all

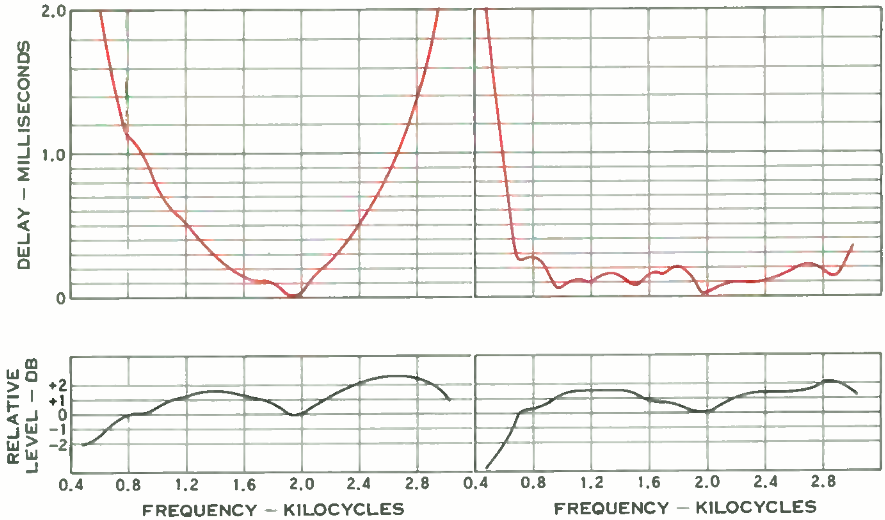

Figure 3. Amplitude and delay characteristics of a cable carrier channel before and after equalizing delay. In this 450-mile path, signal was translated down to voice frequencies four times.

the equalization was provided at the end of the 450-mile path. Normally, it is preferred to equalize each section of a multi-section transmission path. This permits all incoming signals to have about the same degree of delay equalization, regardless of the varied routes that may be employed in transmitting a message between two points.

Equalizing the delay is analogous to color-correcting a lens. Simple lenses focus light of different colors to different points—the lens has a different focal length for each color. The degree of this dispersion of light of different colors is different in different types of glass. By selecting the right combination of glasses and lens shapes, a lens can be produced that focuses nearly all colors to the *same* point. Similarly, by using the right combinations of filter elements, delay can be made nearly uniform across a given band of frequencies.

Channels and Channel Capacity

The standard 3000 cycle telephone circuit is an almost universally available type of communications channel, anywhere in the world. Almost all general purpose communications facilities are designed to accommodate voice signals. Accordingly, this bandwidth has been taken into consideration in designing equipment used to transmit telegraph signals and other data from point-to-point. Most such equipment is designed to be used over telephone-type circuits, usually by dividing the single telephone channel into several telegraph channels. Such telephone circuits usually must employ delay equalizers to make them suitable for reliable, high speed data transmission.

Why then the concern over transmission speed? According to Nyquist's formula for maximum signaling speed, a 3000 cycle channel should be capable of carrying 6000 binary pulses per second. Translated to words per minute, and using the standard Baudot or teletypewriter code, this is approximately 8000 words per minute! Furthermore, the information capacity is considerably higher if codes other than binary are used. Using Shannon's formula for maximum channel capacity, which relates information rate to bandwidth and the amount of interfering noise in the system, a channel of 3000 cycles bandwidth and a signal-to-noise ratio (signal power/noise power) of 30 db has a capacity of about 30,000 bits per second:

$$\begin{aligned} \textit{Capacity} &= W \log_2 \left(1 + \frac{S}{N}\right) \\ &= 3000 \log_2 1001 \\ &= 3000\ (9.96) \\ &= 29{,}880 \text{ bits per second.} \end{aligned}$$

Of course, this is ideal, non-surpassable performance, and achievable only by the most elaborate coding. In practical systems we cannot begin to approach that rate of transmission. Such performance would require whole buildings-full of equipment to encode and decode the message. In addition, the time required for encoding and decoding messages would be far too great for practical needs. Although we cannot conveniently transmit information through a 3000 cycle channel much faster than about 3500 bits per second in the presence of normal amounts of interference, our equipment requirements at that rate are quite modest, as indicated in Figure 4.

Conclusions

Although there is an intense and continuing demand for more transmission facilities to enable data processing machines to be connected to one another, speed shouldn't be emphasized for its own sake. The fact that a punched card reader can accept, digest, and print out 90 cards per minute doesn't necessarily mean that it is always economic or desirable to transmit the contents of 90 cards per minute.

An important way of reducing the *need* for a faster data transmission is to transmit only what must be transmitted. Redundancy can be used to reduce errors, but such redundancy must be used systematically. Random redundancy is merely wasteful. Where the flow of material is too great for a slow speed circuit, several slower speed circuits may be cheaper than one high speed circuit of the same bit capacity.

It isn't necessary to transmit repetitive information. One of the basic tenets of information theory is that information is *unpredictable news*. Whatever is already known at the receiving end need not be transmitted. Thus, it isn't necessary to transmit salary information about a man on the payroll unless the unpredictable news is that he has gotten a raise. The central computer can store all the information about the man's salary, deductions, and take home pay under normal circumstances. If he is paid by the hour, all that it is necessary to transmit is the number of hours worked and the man's identifying number. Even a slow speed circuit can handle a very large amount of information if it is reduced to its essentials.

For example, one of the largest integrated data processing systems in America is operated by the Sylvania Electric Company. Their computer and data processing center in Camillus, New York is connected to Sylvania laboratories and factories across the country. The computers store most of the management information required in routine operation of the company; payroll, purchasing information, scheduling and other production data, accounting information, and others. All data

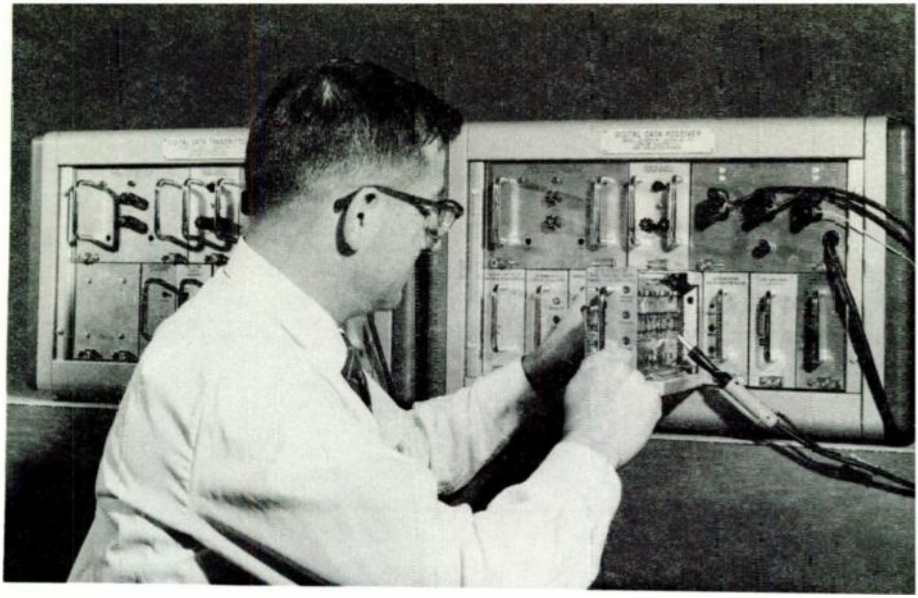

Figure 4. Commercial prototype of high speed data transmission terminals. This equipment has transmitted data at 3360 bits-per-second rate within a single carrier voice channel having a useful bandwidth of less than 3000 cycles. Path length was 450 miles. No errors occurred in transmissions exceeding ten million bits.

are transmitted between different locations over standard 75 bits-per-second teletypewriter channels! Despite the tremendous speed at which the computers operate, the standard teletypewriter circuits are sufficiently fast to transmit all the essential information needed for this efficient operation.

Another criterion for determining the need for fast transmission is the *timeliness* or *rate of obsolescence* of the information to be transmitted. For example, in SAGE defense networks, early warning radars at strategic locations are connected by data transmission circuits to an electronic computer. The computer compares observed flights with data concerning the location and schedule of authorized flights.

Such a data system must operate in *real time*. In this sense "real time" indicates that the information must be transmitted as fast as it is acquired because of its very high rate of obsolescence. When a radar is tracking high speed aircraft, each aircraft's position is known each time it is illuminated by the radar beam. Between sweeps, however, the aircraft may change position, altitude, speed, or heading. Obviously, it is vital to get the radar information to the computer without delay. The more detailed and accurate this type of information is, the more bandwidth is required to convey the information on a real-time basis. In the SAGE system, information is transmitted at rates of either 1300 bits or 1600 bits per second.

Where storage and delay are permissible, reduction of transmission speed offers two benefits: error rate may be sharply reduced for a given amount of noise; suitable circuits and equipment are much more universally available, and cost less.

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Next month's issue will describe some of the methods being developed to crowd more information through existing communications circuits.

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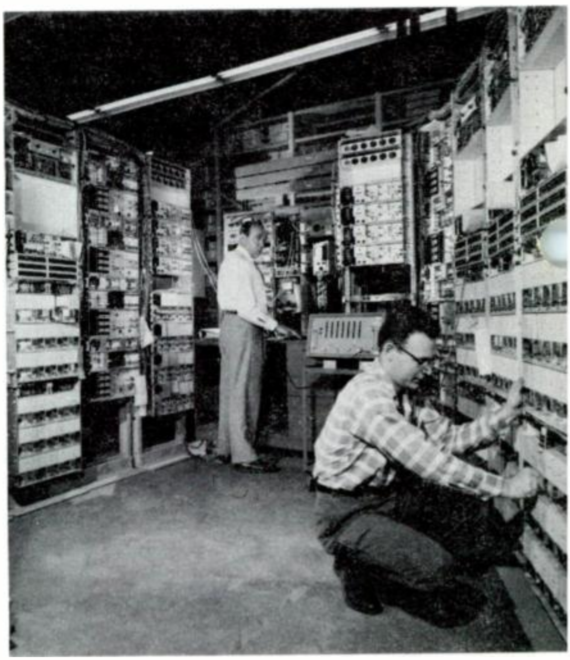

Work has begun on the "Air Com" program to modernize and extend the U. S. Air Force global communications network. First phase of the program involves major overhaul of facilities at nine centers in the U. S. and abroad.

Carrier equipment for "Air Com" is shown being tested at Lenkurt before shipment. Air Force specified that only Lenkurt carrier—or equipment of equal quality—be used on this important project.

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