The Lenkurt Demodulator

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INFORMATION THEORY

and Modern Communications

Information theory began as an academic mathematical inquiry into factors which limit communication. The fantastic growth of man's ability to communicate in the past several decades has confirmed the importance of the inquiry and added the pressures of many important practical problems. Billions of dollars have been spent on communications in recent years and will be spent again to keep up with public demand. Improving the efficiency of communication facilities could channel these funds into providing even greater advances. This article discusses some of the highlights of information theory and how it is related to carrier communications.

Information is a rather nebulous term with different meanings for different people. To the communications engineer, information is anything that is communicated, whether it be the sighs of a moon-struck teen-ager on the family telephone, or the unfeeling telemeter report on the performance of a machine.

Although no one has yet devised an adequate measure of the "information" transmitted by the teen-ager, *information theory* has provided the designers of communications systems with new insight into the intangible commodity with which they work. By providing engineers with a specific measuring stick, information theory enables them to measure the efficiency of their communications apparatus and make improvements. The theory is important not only to conventional communications media, but it has important implications in computers, control systems, and data systems where machines communicate directly with machines.

Information theory studies have revealed two basic approaches to improving communications. One is based on improved coding of the signal to be transmitted; the other stems from new knowledge of the relationship between signal power, noise, and bandwidth. There are indications that both approaches lead to a common goal; the most efficient coding method will possibly be the most efficient way of compressing bandwidth and overcoming noise in a transmission channel.

Communication is concerned with *information.* According to the mathematician, information is *unpredictable* news. Whatever part of the message can be predicted, need not be transmitted. This is carried to an extreme by numbered telegraph codes for birthday greetings and standard commercial expressions. Such codes provide a very efficient form of communication if the "canned" message conveys the desired information.

Not only are languages loaded with non-essentials, but our very speech is highly redundant. Although speech tones may include frequencies up to 10,000 cycles, it is generally accepted that highly intelligible, individual speech requires a bandwidth of only 2500 cycles, with 3000 cycles being preferable, if the speaker's identity is to be well-preserved. Telephone researchers have devised techniques for compressing speech to one-tenth this bandwidth, with little loss of identity.

Voice sounds consist of two basic tones, a "buzz" or larynx sound, and a "hiss" or breath sound. Various combinations and pitches of these two basic sounds make up our speech. Bell Telephone Laboratories' experimental Vocoder takes advantage of this structure by analyzing speech sounds and sending code signals representing the average energy level in various portions of the sound spectrum. At the receiving end, a synthesizer interprets the code and controls a hiss-and-buzz generator to produce a surprisingly life-like re-creation of the original voice.

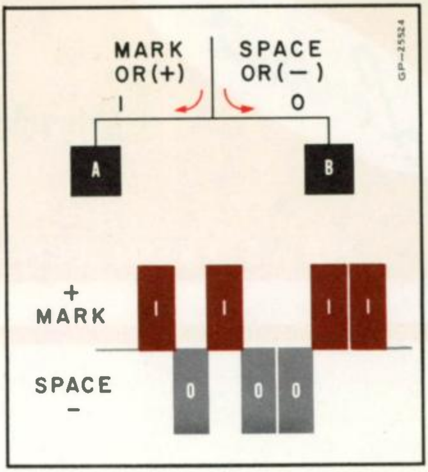

Figure 1. Above, binary code is based on selection between two equally probable alternatives. Mark or space selects A or B. Below, typical polar pulse code. In practical radio or carrier systems, two tones or frequencies may be used for marks and spaces.

A perfect-fidelity transmission of a piano solo might be obtained in a similarly compressed bandwidth if a code were transmitted for each piano key struck. At the receiving end, a player piano with a suitable receiver could re-create the original form of the music. Experimental "gadgets" like these have the serious purpose of improving the efficiency of our communications networks. With such a bandwidth improvement, a carrier system that now accommodates 240 channels could handle 2,400 channels. This would drastically cut the cost of communications and extend service into new, untouched fields.

Communicating In Code

One of the most important basic codes for conveying information is the two-symbol or binary code, such as the mark and space of the teleprinter. This code is particularly suitable for handling by machines. Two clear-cut states, such as "on" and "off" are required. Such a code, distinguishing between two unpredictable states, is the simplest possible. The presence of one of the two conditions conveys one *bit* of information (from *bi*nary digi*t*).

Despite the simplicity of the code, with a sufficient number of bits and enough time to transmit them, anything can be transmitted. A modern teleprinter circuit transmits about 70 bits per second and has a capacity of about 700 bits per second. A telephone channel, however, jumps to a capacity of about 30,000 bits per second, although communication increases only about three-or four-fold. A television channel has a capacity of 40,000,000 bits per second. Figure 2 shows how black or white "bits" can build up a finely-detailed image with many gradations.

A television picture, like speech and other communication, is largely repetition. Much of the tremendous information capacity of a television channel is used in painting the same picture over and over. If it were possible to transmit only the *changes* occurring in the scene, television pictures might be transmitted over ordinary telephone channels instead of requiring special facilities. Of course, in such a system, an abrupt change of scene might appear like a motion picture "dissolve."

A carrier system is similar to the television channel in that it conveys a vast body of information, representing many telephone and telegraph channels. A 240-channel system requires a capacity of 9,600,000 bits per second. New methods of encoding the information for transmission show promise of drastically reducing this requirement. Carrier signals which are a composite of many channels are statistical by nature and are therefore particularly suitable for improved encoding to take advantage of this statistical nature.

Figure 3 illustrates how a statistical concept in coding can reduce the number of bits required for a given message. In Figure 3(a) the letters E, T, A, and I are coded for equal probability. Since there are four letters, a two-bit code is required to distinguish between them. In Figure 3(b) these letters can be re-coded more efficiently if some letters

Figure 2. Printed picture illustrates how continuous shades of gray may be created using only black and white. Process is analogous to reconstructing continuous waveforms from quantized pulses.

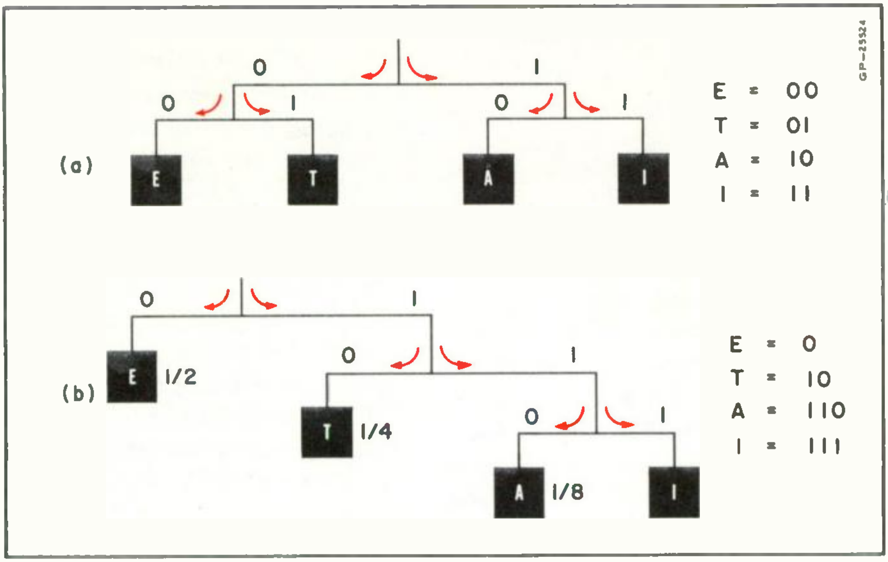

Figure 3. Two methods of coding information. In (a), characters are equally probable. Two bits are required for each. In (b), some characters are known to appear more frequently. Improved coding reduces total number of bits required.

are used more frequently than others. If the message contains, on the average, one-half E's, one-fourth T's, and one-eighth each of A's and I's, an efficient code might be to represent E by **0**, T by **10**, A by **110**, and I by **111**. With this code a typical message TIEEETAE becomes **10111000101100**. The total message contains only 14 bits, or one and three-quarter bits per letter instead of two bits per letter.

Although such a statistical approach might not be practical for individual information channels, it is very practical for use with the great quantities of information found in multi-channel carrier communications. Telephone researchers have shown that spoken and written languages are highly predictable on a statistical basis and therefore provide an excellent opportunity for improved coding.

Chopping a message to Bits

Information theory studies have shown a relatively new modulation method called "pulse code modulation" or PCM, to be nearly ideal as a means of transmission. In this system, information is carried by some form of pulse code. The pulse code system most widely described conveys information by the presence or absence of pulses—variations in the precise amplitude or slope of a waveform do not reduce the information content or the ability of the receiving equipment to obtain all the original information. PCM is unique in that signals can be retransmitted or repeated as many times as desired without introducing any distortion or degradation by noise, provided only that the signal-to-noise ratio is such that the greatest noise peaks will not be mistaken for signal pulses. PCM is very effective in combating noise because it is very difficult for noise or distortion to blur out an existing information pulse, or to simulate a signal pulse.

The signal amplitude range to be transmitted by PCM is divided into a number of standard values or steps. The input signal is sampled periodically to yield the nearest standard amplitude. Thus, actual amplitude A in Figure 4 is transmitted as standard amplitude 2, whereas actual amplitude B would be transmitted as standard amplitude 3. This process, termed information quantizing, introduces a certain amount of error in the transmitted signal, but this error is small if a large number of standard amplitudes are available. At the receiver, error averages out to yield an excellent reproduction of the original waveform. The standard amplitude is not directly transmitted in PCM, but rather is indicated by a code. Thus, each standard amplitude in Figure 4 can be specified by different combinations of pulses in a 3-place code. A code system having 32 standard amplitudes could be specified by a 5-place code. Experimentally, television signals comparable

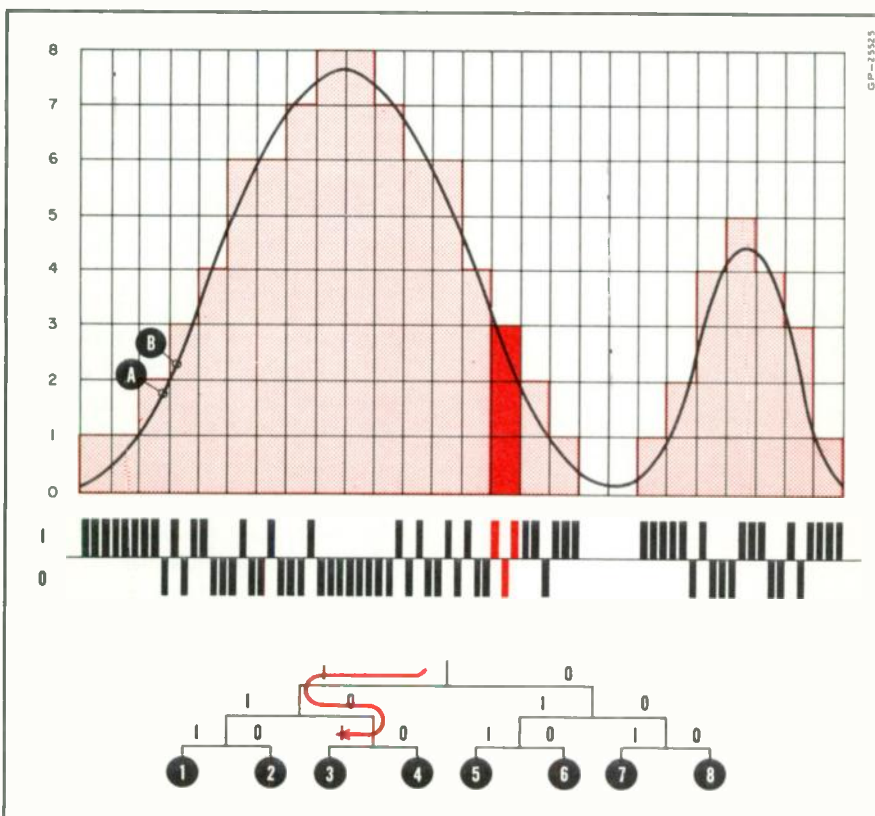

Figure 4. How a waveform may be quantized and converted into a pulse code. Eight standard amplitudes are used, requiring a three-digit code.

in quality to current commercial television have been produced using a 5-digit pulse code.

Currently, PCM continues under investigation. Using conventional pulse coding, it requires considerably more bandwidth than regular single sideband carrier techniques, bandwidth that cannot be spared in the long distance toll circuits for which PCM is otherwise so well suited. Progress is being made in developing codes that reduce bandwidth requirements and permit greater flow of information.

Power, Noise, and Bandwidth

If there were no "noise" to degrade a transmission, there would be no limit to information transmission. By transmitting a perfectly measured voltage to represent information, any desired rate of communication could be achieved. In reality, noise masks the signal and introduces uncertainty as to its exact value. Signal tends to be converted into noise by a process of degradation and distortion. In transmitting many channels of information over a carrier, each channel requires a certain bandwidth in order to distinguish the signal from random noise. Thus, the greater the number of channels, the greater the bandwidth required. However, as number of channels increases, each channel signal is a smaller and smaller portion of the total. As the channel signal gets smaller, it becomes increasingly difficult to distinguish it from background noise unless transmission power is increased.

Information theory studies have revealed the exact relationship between information capacity, signal power, noise, and bandwidth. While these studies have generally confirmed knowledge acquired on an experimental basis, a number of possibilities were revealed that had not been self-evident. It was well known that a smaller signal-to-noise ratio would be acceptable in communications if greater bandwidth were employed, as in FM. It was surprising, however, to discover that in principle, bandwidth could be reduced by increasing signal-to-noise ratio. Heretofore, it was firmly believed that channel bandwidth could never be less than the bandwidth of the original message.

These studies show that there is an ideal method of encoding information for transmission over the noisiest channel at rates up to the theoretical limit, and permitting as low a probability of transmission error as required. Redundancy or repetition reduces error probability. By introducing a controlled amount of redundancy in proportion to the channel noise, the desired transmission reliability can be maintained under the worst conditions, at the cost of reduced transmission rate. If reduced transmission rate cannot be tolerated, more complicated coding can theoretically be employed to keep down the probability of error. Practical limits on complex coding methods make it seem likely that the transmission of redundant information will be the more economical approach to error-free transmission of information.

For many years, television was "just around the corner." The corner was turned a dozen years ago, with profound effects on our economy and pattern of living. Similarly, some of the concepts suggested by studies of information theory promise to have a like effect on tomorrow's communications.

GLOSSARY OF TERMS

In recent years, the fields of communications, information theory, and computer engineering have expanded until, in some applications, they have become one. The language of this rather new area of research draws on all three specialties for its vocabulary and sometimes puts a new interpretation on an old word. Some of the terms often encountered are listed below with their specialized meanings.

BINARY—Anything that is composed of two parts or elements, or which has only two states or conditions; for example, a switch may be either on or off.

BINARY CODE—Any *code* employing only two distinguishable *code elements* or states; mark-space and on-off are examples of *binary codes.*

BINARY DIGIT—A unit of information content; one element or *bit* of a binary or two-element code; mark and space are examples of *binary digits* used in communications codes.

BIT—Commonly used short form of *bi*nary digi*t;* see above.

CHANNEL CAPACITY — The maximum possible information rate through a channel. *Channel capacity* is often stated as the maximum number of *bits* per second that may be transmitted through the channel.

CLOCK—The primary source of synchronizing signals for a computer data system or data transmission system. In high-speed systems, the *clock* may be an oscillator, the output of which is used as a reference or timing frequency by the system.

CODE—A system for representing that which is to be transmitted. For example, Morse *code* may be used to represent letters in telegraphy. Words and language may be considered a way of *coding* ideas.

CODE CHARACTER—One of the elements which make up a *code* and which represents a specific symbol or value to be encoded. Dot-dot-dot-dash is the Morse *code character* for the letter *v.*

CODE ELEMENT—One of a set of parts of which *code characters* may be composed. Mark or space, dash or dot, are examples of *code elements.*

COMPUTER—A machine for carrying out calculations, or for performing specified changes or transformations of *information.* Some types of decoders operate on *computer* principles.

DATA—Information, usually originating as numbers, values, or digital symbols. *Data* usually excludes speech, music, or other continuous-wave information, even when converted to digital form for transmission.

ENTROPY—Disorder; reduction from an easily distinguishable condition to a less easily distinguishable condition; equal and opposite to "amount of information." An example of entropy is the gradual distortion and loss of a signal pulse as it travels down a long wire or cable.

ERROR—A false transformation of *information;* a mistake in transmission; improper alteration of *information;* an incorrect step, process, or result in transmitting *information.*

INFORMATION—News, intelligence; that which improves or adds to a representation. *Information* is an unpredictable event or item. If the transmission specifies something already known to the receiver, it is not *information.*

REDUNDANCY — Added or repeated *information* employed to reduce ambiguity or *error* in a transmission of *information.* As signal-to-noise ratio decreases, *redundancy* may be employed to prevent an increase in transmission *error.*

QUANTIZE—To convert a continuous variable, such as a waveform, into a series of levels or steps. There are no "in between" values in such a *quantized* waveform. All values of signal are represented by the nearest standard value.

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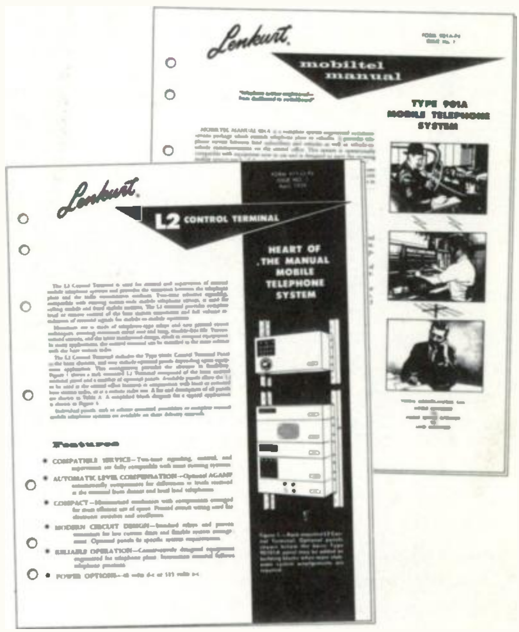

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