The Lenkurt® Demodulator

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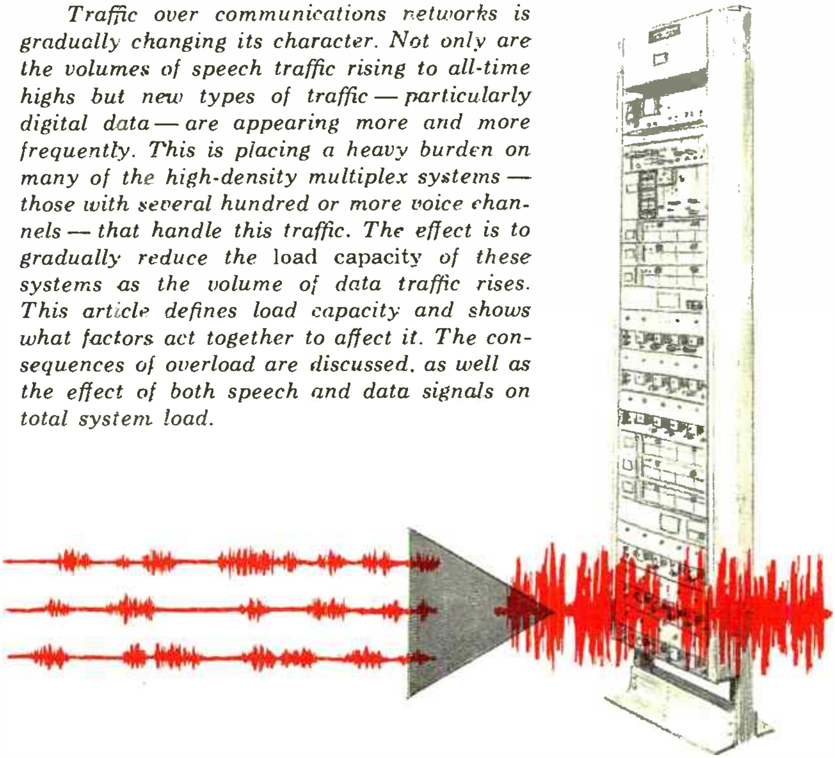
LOAD CAPACITY

of high-density multiplex systems

Traffic over communications networks is gradually changing its character. Not only are the volumes of speech traffic rising to all-time highs but new types of traffic — particularly digital data — are appearing more and more frequently. This is placing a heavy burden on many of the high-density multiplex systems — those with several hundred or more voice channels — that handle this traffic. The effect is to gradually reduce the load capacity of these systems as the volume of data traffic rises. This article defines load capacity and shows what factors act together to affect it. The consequences of overload are discussed, as well as the effect of both speech and data signals on total system load.



WHAT is a 600-channel multiplex system? If this question were asked of people only lightly engaged in communications work, the answers would probably be as varied as they were numerous. A typical answer might be: "A 600-channel multiplex system is one that can carry 600 voice-frequency signals simultaneously — one signal in each voice channel." This seems logical. Such a system does have 600 channels and each channel is capable of carrying a signal. Surprisingly enough, this answer is almost never true. Few high-density systems can approach carrying signals simultaneously on all channels without being severely overloaded. Such an extreme capability is not required in most of these systems, since traffic will rarely be present in all channels at once. The traffic-handling capability, or *load capacity*, of a high-density multiplex system, therefore, is based on the probable signal load at the time of heaviest traffic, rather than the maximum load that could occur.

Load capacity can be defined as the volume of traffic a system can handle without undue distortion or noise. The exact meaning of "undue" varies, depending on the quality of service required, but generally it is the point at which interference seriously affects either the accuracy or the intelligibility of the transmitted information.

Many factors act together to determine load capacity. The physical makeup of the major circuit elements — amplifiers, modulators, and demodulators

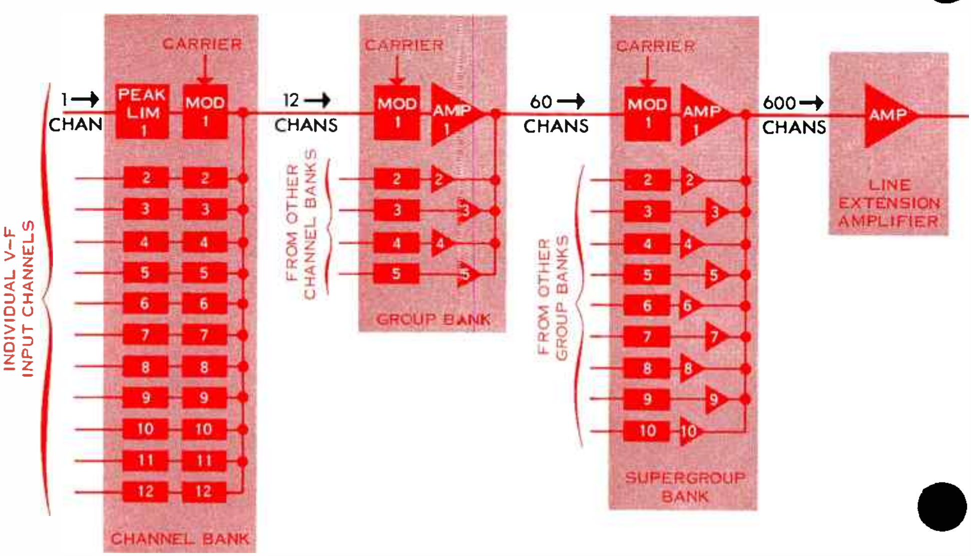


Figure 1. Arrangement of the major active circuit elements in the transmit portion of a typical 600-channel multiplex system. Many elements are common to more than one voice-frequency channel.

— fixes the maximum signal load a system can handle. This factor is constant in any system. The types and quantities of signals carried by a system determine the total signal load. Some types of signals impose much heavier loads on multichannel systems than do others. Data and telegraph signals, for example, normally present a continuous load, while speech, which is quite sporadic, does not. If the number of channels carrying data or telegraph signals exceeds that which a system was designed to carry, then other voice channels may have to be disconnected from service to prevent overloading. This, of course, reduces the system's load capacity.

Transmission requirements of a particular network also affect load capacity. These requirements set the levels of input signals to a multiplex terminal and establish the maximum permissible noise level at the terminal output. If signals have to be applied at high levels, or if noise requirements are unusually stringent, then the load capacity may be effectively reduced.

Speech is the predominant type of traffic in most multiplex systems. Consequently, most systems are designed around the characteristics of speech signals and the statistics of telephone talkers. Allowance is usually made for signaling tones, pilot signals, carrier leak, and relatively small amounts of telegraph traffic. Probability has played an important part in arriving at a suitable load capacity for these systems. As stated previously, these systems are designed to handle the probable signal load at the time of heaviest traffic, rather than the maximum load that could occur. Of course, there will be instances when the total load exceeds the design limitations. These instances, called the *periods of overload*, must not occur except for a small percentage of the time if a system is to provide adequate service.

Effects of Overload

A multiplex system allows several signals to be transmitted simultaneously over a single transmission medium. Most high-density systems use a frequency-division form of multiplexing, where individual input signals are translated to separate positions in the frequency spectrum by means of amplitude modulation. The lower sideband of the frequency-translated signal is usually transmitted, while the carrier and upper sideband are suppressed.

In these systems, many voice channels are handled by common amplifiers, modulators, and other active circuit elements. If a system were perfect, each of these elements would be completely linear, and a signal at the output of any element would be a faithful reproduction of the input signal, with nothing added or taken away. For practical reasons these are ideals that are approached but never fully realized. All active elements are non-linear to some extent and induce a certain amount of distortion into the signal. In a well-designed transmission system, distortion is simply held to within limits that are acceptable to the user.

Of all the active circuit elements in a multiplex system, multichannel amplifiers contribute the most distortion and are most likely to overload when input signals reach high levels. In a typical system these amplifiers may be common to anywhere from a few voice channels to several hundred, and have a frequency bandwidth of from several thousand to well over four million cycles per second. Over such a wide band of frequencies, amplitude response and phase shift will not be uniform. Most amplifiers use negative feedback to improve linearity, but practical considerations cause amplifier performance to be somewhat less than ideal.

When signals of different frequencies are applied to an amplifier, the output contains not only the input frequencies but an almost infinite number of other frequencies. Harmonics of the input frequencies appear in the output. In addition, an amplifier generates a great many intermodulation products including not only the sums and differences of the original input frequencies but also the sums and differences of their various harmonics. Since these products were not present in the original input signals, they are the distortion caused by the amplifier's nonlinearity. The more nonlinear the amplifier the greater the power of the distortion products.

As long as the amplifier is operated within its dynamic range, power levels of the distortion (or intermodulation) products normally will be too low to interfere greatly with the original input signals. Second-order products (A + B, A − B, 2A, and so on) will have the greatest amplitude, followed successively by third-order products and higher orders. However, with every 1-db increase in rms ouput power, second-order products increase in power by 2 db, third-order products by 3 db, and so forth. All products follow a power series increase until the power of the input signal reaches a certain critical point—the *breakpoint* of the amplifier.

Above the breakpoint, second- and third-order intermodulation products quickly rise in power. But the biggest power rise is in higher order products. These products jump abruptly from very low levels to levels very near those of the .second- and third-order products. If the amplifier has a bandwidth of one octave or less, most even-order

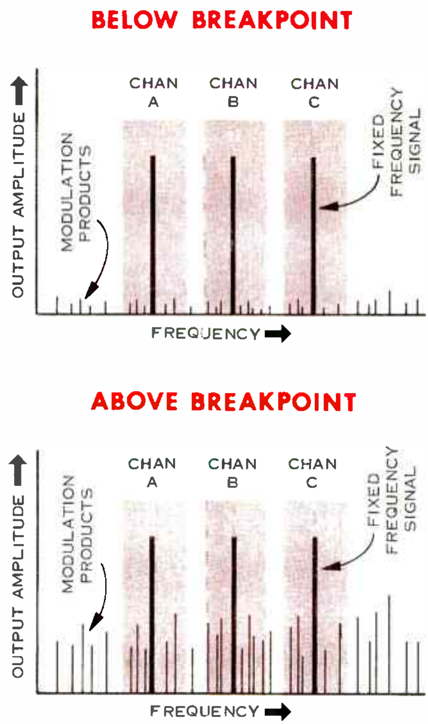


Figure 2. Signal distortion in a multichannel amplifier. Below the amplifier breakpoint, modulation products falling within a channel bandwidth are at relatively low levels and do not significantly interfere with the input signals. But above the breakpoint the magnitude of these products increases dramatically, causing excessive noise in the channels.

products will fall outside the passband, and only the odd-order products falling within the passband greatly interfere with the impressed signals. In a wideband amplifier both even- and odd-order products may cause interference. Sizable disturbances may occur in nearly all channels handled by the amplifier. They appear not as distortion of the impressed signals, but rather as a type of noise whose level depends on the load in all channels.

The breakpoint, therefore, defines the instantaneous load capacity of an amplifier. The CCITT (International Telegraph and Telephone Consultative Committee) defines the breakpoint as the power at the output of an amplifier, at which a 1-db increase in input signal power causes a 20 db or more increase in power of the third harmonic. There are, however, a number of other definitions. The breakpoint of a system depends on the quality of service required. With speech, experience has shown that adequate service will be achieved if during the *busy traffic hour* the sum of all periods of overload does not exceed more than 1 percent (36 seconds).

Speech Loading

The total load applied to a multichannel amplifier is simply the sum of the loads in the individual channels. It might appear that the total speech load in an amplifier handling N number of voice channels is simply N times the load in a single channel. This, however, is not the case. There are certain peculiarities about speech transmission that tend to reduce and stabilize the total load as the number of channels increases. The net result is that multichannel amplifiers, particularly those which handle a great many channels, need not be designed to handle an extremely wide range of amplitudes — as broad a range, for example, as would be required for a single-channel amplifier. This permits using amplifiers that are considerably less complex, thereby reducing their cost.

With speech, three factors act together to determine the total load:

- the number and distribution of channels actively transmitting speech
- the volumes of speech in the individual channels
- the distribution of speech signal peaks

The first two factors cause rather slow variations in the total load and combine to equal what is known as the *maximum rms load* on the amplifier. The third factor causes instantaneous variations and results when peaks in the speech of several talkers occur at the same time.

Numerous studies have shown that in high-density multiplex systems all voice channels will rarely, if ever, be actively transmitting speech at a given instant. Some channels will be completely *idle,* meaning that they are available for an operator to complete a call. Other channels will be *busy,* in that a connection will have been made between two parties; but there will be no speech in the channel at that instant. Still others will be *active,* meaning that they are busy and speech is present in the channel. It is only the active channels that, at a given instant, contribute to the total load on a multichannel amplifier.

Both the total number of simultaneously active channels and their distribution throughout a system are questions of probability. In an N-channel system, it is possible for either zero or N channels to be simultaneously active, or for all active channels to be grouped in such a way that the total load is concentrated at a few amplifiers or within a narrow frequency band — but it is not very probable. Such extremes become even less probable in systems with greater numbers of channels. In high-density systems, the number and distribution of active channels will vary, but in most cases only between narrow limits.

Several years ago measurements were made on large numbers of telephone channels to determine exactly what per-

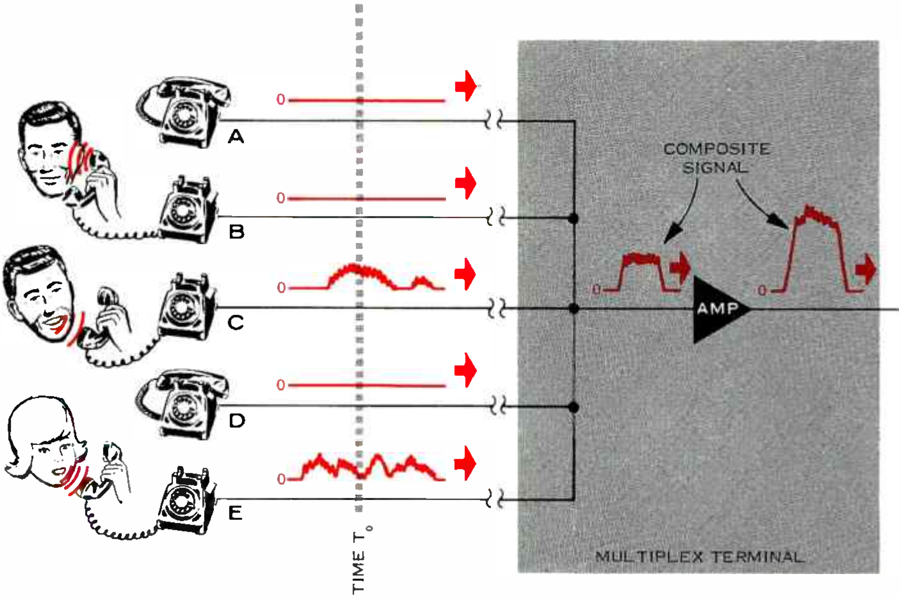


Figure 3. At a given instant in time, speech will not be present in all multiplex voice channels. Some channels will be completely idle (A and D), some will be busy but there will be no speech in the channel at that instant (B), and some will be actively transmitting speech (C and E). It is the active channels only that contribute to the total load on a multichannel amplifier.

centage of the busiest traffic hour a channel might be active. This percentage is called the *activity factor*. Results showed that in high-density systems the largest percentage of the busy hour that this might occur is about 25 percent. For smaller groups of channels this percentage may be larger, but it is highly unlikely that any increase in group size would change it appreciably. This activity factor is considered standard for multiplex systems that carry predominantly speech traffic.

Volumes of speech in active voice channels also affect the total load. Speech volumes are not constant in a channel, but vary considerably, depending on the characteristics of the talker's speech and the loudness of his voice. Obviously a system can tolerate a great many more soft talkers than it can loud talkers. An unusually high percentage of loud talkers can overload a system just as easily as an excessive number of active channels.

Speech volume is an approximate measure of the average speech energy introduced into the voice channel. This energy varies with the words and syllables spoken, but is generally concentrated in the lower voice frequencies between about 250 and 1000 cps. The amount of energy in speech is quite small compared to energy from other sources. An incandescent lamp, for example, expends almost *three million* times as much energy each second as a person speaking a simple six- or seven-word sentence. Indeed it would take 500 people talking continuously for one year to produce enough energy to heat a cup of tea!

Speech energy is commonly rated in terms of the intensity level of a speaker's voice measured one meter from his mouth. The American Standards Association has adopted a reference intensity of 10^{-16} watts per square centimeter for such measurement. Numerous experiments have shown that the *average speech intensity* for all people is about 66 db above the reference intensity, with men having a slightly higher average level than women. When a person talks as loudly as possible, this level can be raised to about 86 db; and when talking as softly as possible, it can be lowered to nearly 46 db; so that from a soft whisper to a loud shout, there can be a range of 40 db.

When several channels are combined into a group, such wide variations in average power tend to average out. In groups of 64 or more channels, the total rms load will vary quite slowly, despite rather wide power variations in the individual channels. Only when an unusually high percentage of either loud or soft talkers is present will the total rms load reach extreme levels.

Changes in active channels and speech volumes are concerned only with the maximum rms load on a multichannel amplifier, causing more and more gradual variations as the number of channels increases. But it is the total input voltage applied to an amplifier, and not just the rms portion, that determines whether or not the amplifier will overload. This total voltage is the vector sum of the instantaneous voltages in the separate channels and thus is a function of both the phase and amplitude of each speech signal.

Instantaneous voltage in an active voice channel fluctuates widely, even when the volume of speech in the channel is constant. The fine structure

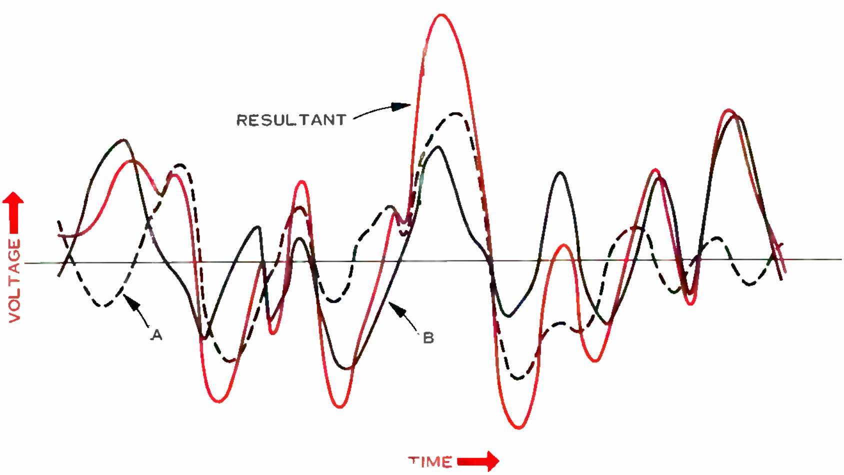


Figure 4. Phase addition of two random speech signals (A and B). High voltage peaks appear in the resultant whenever the individual signals peak together.

of individual speech sounds, and the differences between successive syllables and between vowel sounds and consonants, cause instantaneous variations in speech voltage. Extremes reached by speech signal peaks are very dramatic, often reaching as high as 100 times the average levels. If these peak variations are coupled with the 40-db range in average speech volumes, the peak power can conceivably range as much as 70 db — corresponding to a power ratio of *10 million to 1*.

When several channels are combined into a group, peaks tend to average out as do variations in average power. However, this averaging does not occur in all instances. Since many different frequencies are transmitted, the phase relation between these frequencies varies randomly. Sometimes several frequencies will reach a peak together, causing a momentary rise in total voltage. At other times, the various frequencies may combine to lower the total voltage well below average. It can be shown mathematically that as the number of channels increases, the possibility that several frequencies will peak together decreases. Nevertheless, it always exists and must be considered in the design of multichannel amplifiers.

To prevent a few loud talkers from upsetting the balance between probable maximum instantaneous load and the load capacity of the system, individual voice channels are usually provided with peak limiters. With these devices, excessive voltage peaks are prevented from entering the system.

Data Loading

In recent years the volume of digital and analog data transmitted over communications networks has shown a substantial rise. Businesses are transmitting more data over commercial and private networks than ever before. Facsimile, teletype, and graphics are being carried more and more frequently. Consequently, a multiplex system may be called upon to handle more data than it was designed to carry, thereby decreasing its load capacity.

As mentioned earlier, most multiplex systems are designed to handle predominantly speech traffic, so design criteria are based on statistical probability. Human speech is extremely random. This characteristic, together with the fact that only a small percentage of the voice channels are active at a given instant, allows speech signals to average out in high-density systems, thereby reducing and stabilizing the load variations on multichannel amplifiers. These criteria, while in most cases suitable for a limited amount of data transmission, are far from being optimum when larger volumes of data become involved.

For one thing, data does not flow randomly into a voice channel, as does speech. The flow is either continuous, as with frequency-shift telegraph transmission, or interrupted, as with on-off type data signals. Data signals also are more or less of constant amplitude, in contrast to the wide level variations of speech. Thus, the average level of a data signal is considerably higher than that of speech, and imposes greater loads on amplifiers common to many channels.

To compensate for an excessive number of data signals in a multiplex system designed primarily for speech, one of two steps can be taken: either the levels of the data signals must be reduced; or some of the voice channels must be *dropped* or disconnected. The first alternative is not too desirable, since the data signals may suffer a decrease in signal-to-noise ratio and, consequently, an increase in error probability. The second alternative simply decreases the number of channels available for connection.

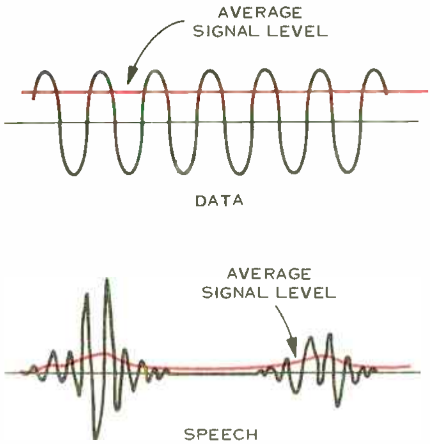


Figure 5. Data signals flow continuously and evenly into a voice channel, while the flow of speech is sporadic. Thus data has a much higher average level than speech and imposes more severe loads on multichannel amplifiers.

Determining Load Capacity

The load capacity of a high-density multiplex system depends on the types and quantities of signals the system must carry. In designing a system, extensive traffic studies are made to determine the quantities of speech, telegraph, and data signals to be handled. Based on these studies, a suitable loading formula is derived, and the power-handling capability of the system is calculated.

In actual loading calculations the input level for each type of signal must be specified. Experience has shown that the average speech power at the input to a voice channel is about −16 dbm0 (16 dbm below the power at the so-called *zero transmission level point*). Although peaks in speech power may reach high levels, tests indicate that they will not exceed −3 dbm0 more than 1 percent of the time. The average levels of telegraph and data signals are normally higher than the average level of speech. Telegraph signals are just about standardized at a level of −8 dbm0 at a channel input. Standard levels for data signals, however, are not yet firmly established. To use existing communications facilities, the input level of a data signal must be compatible with the power-handling capabilities of the average voice channel. Also, the level must be as high as possible for the signal to be relatively free of impulse noise. The exact level for data signals depends on the particular type of data transmission equipment used and the quality of service required. Normally the level selected will be between −5 dbm0 and −15 dbm0.

The above signal levels apply to the loading of a single voice channel. To determine the total load on circuit elements common to many channels it is necessary to calculate the sum of the individual channel powers. When speech is the principal type of traffic, loading formulas recommended by the CCITT may be used to determine the multichannel load. These formulas give the mean absolute power (P_m) of the distributed speech signals that the system must be capable of carrying. The signal power, as measured at the zero transmission level point, depends on the number of channels involved, and is calculated from one of two formulas:

$P_m = -15 + 10 \log N$ *(for N greater than 240 channels)*

$P_m = -1 + 4 \log N$ *(for N between 12 and 240 channels)*

where N is the total number of channels in the system. The formulas include a small margin for loads caused by signaling tones, pilot signals, and carrier leak, and are valid for a limited amount of telegraph transmission.

When a substantial amount of telegraph or data is involved, the CCITT formulas may be insufficient for determining the total system load, although they may be used to determine that portion of the load imposed by speech signals. The loads imposed by telegraph and data signals must be computed from other formulas. One formula that may be used to compute both loads is

$$P_m = P_c + 10 \log N$$

where

P_m = *rms power of the multichannel signal*

P_c = *rms power of the input data or telegraph signal, referenced to the zero transmission level point*

N = *the number of channels carrying data or telegraph signals*

The method of determining load capacity in Lenkurt's 46A multiplex system provides an example of how loading calculations are actually made. The 46A, because of the expected increase in data traffic, was designed to carry substantially more data (or telegraph) than allowed for in the loading formulas recommended by the CCITT. It was decided that the 46A should be capable of carrying speech in 75 percent of its channels, telegraph in 17 percent of the channels, and data in 8 percent.

Two important criteria were first established: the levels of telegraph and data signals at the input to each voice channel; and the maximum noise level at the output of the system. The standard level of −8 dbm0 for telegraph signals was selected, while a level of −5 dbm0 was selected for data. Actually the −5 dbm0 level is probably the highest level at which a data signal would be applied. For the total noise contribution, a design level of 23 dba0 (F1A weighted) was selected. This is the level recommended by the CCITT as the total noise contribution of a pair of terminals, when these terminals are part of a long-haul transmission system. The reference level, or 0 dba0, is equivalent to a 1000-cps tone with a power of −85 dbm.

For a single channel, speech signals impose the greatest load. Elements in a channel are not designed to carry only the average speech level of −16 dbm0, since the elements would be overloaded about 50 percent of the time. However, as stated previously, these elements will not overload more than 1 percent of the time if the channel is designed for an input level of −3 dbm0. This level was selected for the 46A. Telegraph and

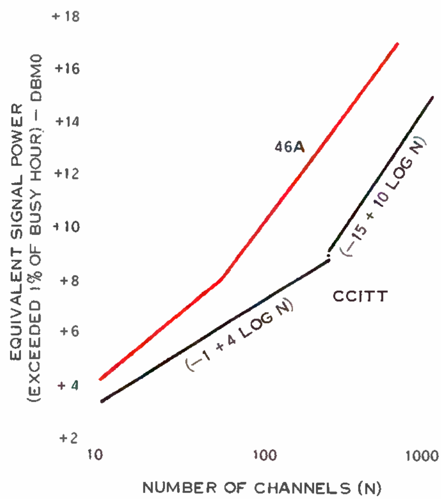


Figure 6. A comparison of the load-handling characteristics recommended by the CCITT and the characteristics of the Lenkurt 46A. The 46A will carry substantially more data traffic than allowed for in CCITT recommendations.

data signals would be applied at levels lower than −3 dbm0 and thus did not influence individual channel design.

In the 46A, considerable advantage was taken of the statistical distribution of speech signals in computing the total speech load on circuit elements common to many voice channels. CCITT loading formulas were used for this purpose. The total load imposed by data and telegraph signals was computed using the general loading formula for these signals. With data, P_c was made to equal −5 dbm0, while with telegraph a value of −8 dbm0 was assumed. Adding the powers of these services for the total number of channels in the system gives the total system load. When more than 240 channels were involved, the following formula was used:

$$P_m = -11 + 10 \log N$$

As stated previously the 46A was designed to carry 75 percent speech, 17 percent telegraph, and 8 percent data. However, this was only a design objective. It assumed that the input levels are −5 dbm0 for data and −8 dbm0 for telegraph, and that 23 dba0 of noise is the maximum allowed at the output. There are many other combinations of signal levels that result in the same total load on the system. For example, 67 percent of the 46A channels will carry data signals at a −5 dbm0 level, if the remaining 33 percent of the channels are disconnected from service. And if the input level of each data signal is reduced from −5 dbm0 to −10 dbm0, the 46A will carry data on 100 percent of its channels, and still have an output noise level that does not exceed 23 dba0.

If better noise performance is needed, the loading of the 46A may be adjusted accordingly. For example, if all channels are used only for speech traffic, then the output will contain approximately 19 dba0 of noise. This same noise level is also possible with data on *all* 46A channels, providing each data signal is applied at approximately −15 dbm0. However, problems may arise if data signals are applied at too low a level. Impulse noise may be too great and cause excessive errors to appear in the transmitted data.

Future Needs

In coming years, the volume of data transmitted over commercial telephone circuits should rise dramatically. As the cost of computers and data processing machines decreases, putting them within the reach of more and more businesses, data traffic will become more prevalent in telephone circuits. More widespread use of dial-operated data transmission sets, which permit fast and economical data transmission, will accelerate the pace even faster. Prominent leaders in the communications industry recently estimated that within ten years the volume of data transmitted over telephone circuits will equal, and possibly surpass, the volume of speech traffic. One thing is certain — there is an ever-growing demand for multiplex systems having a load capacity greater than today's recognized standards, and this demand is sure to increase in future years.

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