The Lenkurt Demodulator

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MULTIPLEXING AND MODULATION

In Carrier Telephone Systems

Part II

The use of amplitude modulation in frequency-division multiplexing was discussed in the first of this two-part article. Because of its widespread usage in toll applications, single-sideband suppressed carrier has become almost synonymous with frequency-division multiplexing. However, current applications of carrier—such as rural subscriber and exchange systems—have made other types of modulation and multiplexing attractive.

In this article, frequency modulation and its use in frequency-division multiplexing is considered first. Then, time-division multiplexing and some of the modulation methods used in this type of multiplexing are discussed.

Although frequency-division multiplexing is often associated with amplitude modulation, the various types of angle modulation may also be used in frequency-division multiplexing applications. Angle modulation is the general term used to describe any form of modulation in which the frequency or phase of a sinusoidal carrier wave is controlled by the modulating wave. Frequency and phase modulation are the two types of angle modulation most commonly used. While these types of angle modulation are somewhat different, they are also closely interrelated. In fact, both are often used in a single modulation system. Because the basic considerations are similar, the following discussion will be restricted to frequency modulation.

Frequency Modulation

Frequency modulation (FM) is the process in which amplitude changes of the modulating wave are used to vary the instantaneous frequency of the carrier wave from its unmodulated value. An example of the action of the modulating wave on the carrier wave to produce a frequency-modulated output wave is shown in Figure 1.

The magnitude of frequency change for a given amplitude of the modulating signal is called *frequency shift*, fre-

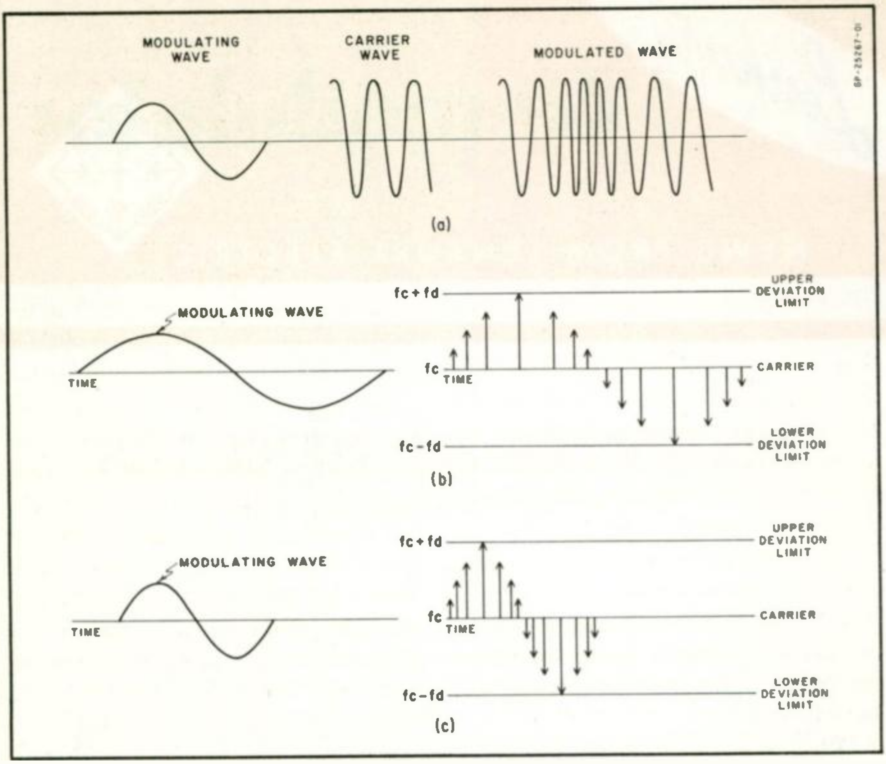

Fig. 1. Frequency Modulation. Both (a) and (b) show how the carrier frequency varies with the amplitude of the modulating wave. A comparison of (b) and (c) shows how the deviation rate is controlled by the frequency of the modulating wave.

quency swing or frequency deviation. However, the last two terms are also often used to define other properties of the change in frequency. *Frequency swing* is normally reserved to denote the maximum frequency shift that occurs when a sinusoidal modulating wave is employed; *frequency deviation* is the maximum value of frequency shift permitted by equipment design, and is also called *peak deviation*. The term frequency deviation is also often used to denote the instantaneous difference between the instantaneous frequency of the modulated wave and the carrier frequency.

While frequency shift is controlled by the amplitude of the modulating wave, the rate at which the carrier frequency is shifted, called *deviation rate*, is controlled by the frequency of the modulating wave. If a carrier of 1 megacycle is modulated by a 1000-cycle sinusoidal modulating signal, the frequency swing that will occur will depend upon the amplitude of the modulating wave. If the frequency swing is 500 cycles for a given amplitude, the carrier will swing between 1,000,500 and 999,500 cycles at a rate of 1000 cycles per second. If a signal of a different frequency but same amplitude is used, the frequency swing will still be ±500 cycles from the carrier, but the deviation rate will be equal to the frequency of the modulating wave. This is shown diagrammatically in Figure 1.

Bandwidth

Since the frequency shift is dependent upon the amplitude of the modulating wave, it would appear that the bandwidth required for FM transmission could be made considerably less than that of the modulating wave. However, the individual cycles of a modulated wave obtained from an FM modulator are not sinusoidal because of the instantaneous variations in frequency which occur during modulation. An analysis of the modulated wave shows that this complex wave contains a large number of sidebands rather than the two normally associated with amplitude modulation.

Where a single sinusoidal modulating wave is used, the spectrum of the modulated wave is symmetrical with respect to the carrier frequency. In this case, the sideband frequencies are displaced from the carrier by integral multiples of the modulating frequency. For example, a 1000-cycle modulating wave would produce a first-order pair of sidebands that differ from the carrier frequency by 1000 cycles, a pair of second-order sidebands located at 2000 cycles on either side of the carrier as well as higher order sidebands. This is illustrated graphically in Figure 2.

If a more complex modulating wave —such as more than one sinusoidal signal or speech— is used, the frequency spectrum of the modulated wave becomes very complicated. The sideband frequencies present include not only those that would be obtained with each modulation frequency acting separately, but also various combination frequencies. However, although complex modulation greatly increases the number of frequency components present in the frequency-modulated wave, it does not widen the bandwidth occupied by the high energy portion of the wave.

Although the total bandwidth of a frequency-modulated wave is quite large, the higher-order sidebands often contain only a small portion of the total wave energy. In these cases, the actual bandwidth can therefore be reduced considerably without introducing un-

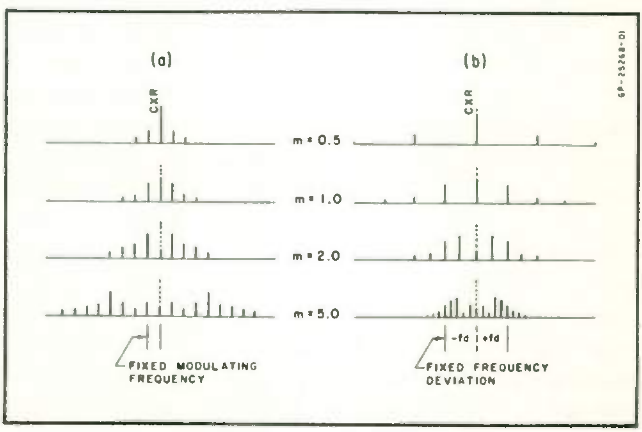

Fig. 2. Energy distribution in an FM wave with a sinusoidal modulating signal: (a) distribution as frequency deviation is increased with modulating frequency constant; (b) distribution as modulating frequency is decreased with frequency deviation constant.

due distortion. The energy distribution depends upon the amplitude of the different frequency components. Component amplitudes, in turn, are related to the modulation index, and may be calculated with the aid of a table of Bessel's functions. The results of a number of such calculations are shown graphically in Figure 3, from which the bandwidth for a variety of conditions may be determined. Bandwidths determined from Figure 3 will contain all but about 1 per cent of the energy in the modulated wave. The loss of 1 percent of the energy will cause distortion. Although the distortion introduced can be tolerated in some applications, in others the distortion requirements are more severe, and a greater proportion of the energy must be included. For these cases, a detailed analysis is made, and Figure 3 is not used.

With reference to Figure 3, some useful rules can be derived for determining the approximate bandwidth required for transmission of a frequency-modulated wave. When the modulation index is greater than 1, the bandwidth is equal to twice the sum of the frequency deviation plus the modulating frequency. Although not shown in Figure 3, as the modulation index decreases to values of 0.5 and below, the bandwidth becomes essentially equal to twice the modulating frequency. In this last case, the bandwidth is the same as for an amplitude modulated wave.

Noise Advantage

Because both methods are used in frequency division multiplexing, the advantages and disadvantages of frequency modulation are normally expressed in terms of similar characteristics in amplitude modulation. On this basis, the chief advantage of FM is in its ability to exchange bandwidth occupancy in the transmission medium for improved noise performance.

The noise-power reduction advantage of FM over AM for random noise is often given as $R = 3\, f_d{}^2/B^2$, where f_d is the frequency deviation and B is the output bandwidth of the receiver. (B is equal to the highest modulating frequency.) This advantage is also expressed in terms of FM advantage *(db of quieting)* and may be written as $db = 10 \text{ Log } 3f_d{}^2/B^2$. For example, for a frequency deviation of 3 kc and a 3-kc modulating signal, a random-noise reduction advantage of about 4.8 db is obtained. In both equations, 100 percent amplitude modulation is assumed and the comparison is made for average output power.

On the basis of the same peak power at the transmitter, SSB-SC has a noise advantage over AM of about 8:1 (approximately 9 db). However, when peak power is used as the basis of comparison, FM has an additional 4:1 advantage (total of approximately 15 db) over AM than that given by the above equation. Therefore, on a peak power basis, the noise advantage of FM as compared to SSB-SC is $R = 3f_d{}^2/2B^2$.

In addition to noise advantage, FM exhibits a characteristic often called *capture effect.* Where two signals in the same frequency band are available at the receiver, the one appearing at the higher level is accepted to the near exclusion of the other.

Improvement Threshold

The noise advantage of FM is obtained for normal signal and noise lev-

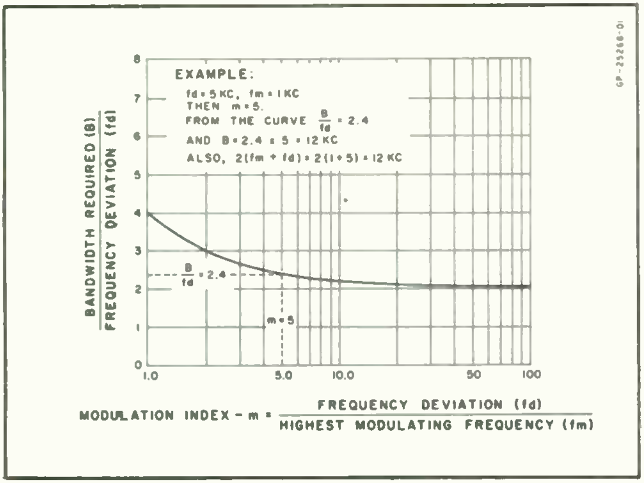

Fig. 3. From the above curve the bandwidth for different modulation indexes of an FM system can be determined. All sideband components except those having less than 1 percent of the wave energy are included.

els at the input to the receiver. And this advantage increases as the frequency deviation (modulation index) is increased. However, as the peak signal level is decreased to that of the peak noise level, there is a rather sharp transition between good and poor signal-to-noise ratios. The point at which this transition occurs is often called the *improvement threshold* (sometimes shortened to threshold).

Although the noise advantage increases as the modulation index is increased, the corresponding increase in bandwidth increases the noise. For large bandwidths, the threshold becomes more critical and is reached at higher signal levels. The optimum value of modulation index is thus a compromise between service range and noise advantage.

Other Features

Other features of FM make its application to frequency-division multiplexing attractive where bandwidth is not a critically limiting factor. These are: (1) separate regulation is not necessary since in a properly designed FM receiver, the output signal level is insensitive to input signal level variations above threshold level; and, (2) synchronization is not a problem because of the detection method.

Time-Division Multiplexing

Although less well known because of its relatively limited usage, time-division multiplexing is the most direct and is basically the simplest multiplexing method. In this method, the circuits to be transmitted over a common transmission medium need not be connected together as in the frequency division case, but are arranged so that each circuit is successively connected to the transmission medium for a short time interval. An example of a technique for accomplishing this purpose is shown in Figure 4.

A commutator or other type of switching device may be used, and in the earlier systems motor-driven commutators were employed. Most present-day multiplexing equipment uses electronic switching and gating techniques.

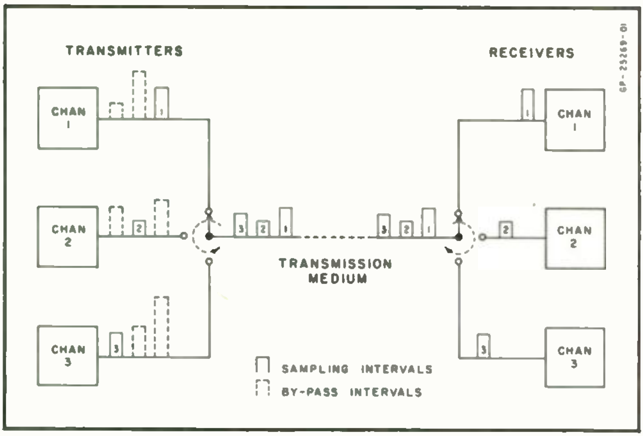

Fig. 4. Time-Division Multiplex. Samples of the input wave are transmitted by successively connecting each circuit to the transmission medium.

Regardless of the switching method, it is apparent that for each circuit the input wave is broken up into a series of pulses called samples. This is an example of pulse-amplitude modulation, since the amplitude of each sample is directly proportional to the instantaneous amplitude of the modulating wave.

Sampling Rate

Because in time division the modulating wave is repetitively sampled, the questions of how large must the samples be, and how often samples must be taken to retain the intelligence naturally arise. It has been found that the time duration of the sample is not critical, and can be reduced as much as required without appreciably degrading the information. However, the samples must be taken at a rate that is at least twice the highest frequency appearing in the modulating wave. For telephone voice channels, the sampling rate commonly used is 8,000 cycles per second. Or, each circuit is sampled once every 125 microseconds. The 125-microsecond interval between successive samples of one channel may be used by other channels of the system. Theoretically the number of channels that may be obtained is very high.

Bandwidth

However, as the number of channels is increased, the bandwidth required for transmission increases rapidly. The reason for this is that the pulse train spectrum is made up of a fundamental frequency that is equal to the sampling rate (8 kc) and its harmonics, all of which have an upper and lower sideband produced by the modulation process.

The actual bandwidth depends upon a number of factors which must be determined during the design of the system. As an example of the bandwidth required for present day systems, a pulse-amplitude modulated (see Figure 5b) system of 30 channels requires a bandwidth of approximately 1 megacycle. This is about 10 times the bandwidth of the intelligence (4 kc x 30 = 120 kc), and severely restricts the application of this type of modulation.

Much work has been expended on the reduction of the bandwidth required in time-division systems, and by using pulse-coding techniques and appropriate filtering of the transmitted signal the bandwidth can be reduced to approach that required for the intelligence. However, the equipment necessary to accomplish this complicates the terminal design, and some of the advantage of simplicity of the multiplexing method is lost.

Synchronization

From the elementary diagram of Figure 4, it is apparent that synchronization is relatively critical in time-division multiplexing, and in time division systems a means of maintaining synchronization is normally provided. A common method of doing this is to transmit synchronizing pulses —often called marker pulses— at the beginning of each frame. A frame is the interval occupied by one complete set of pulses, and in this case the frame is made up of a marker pulse and one pulse from each channel. This is shown diagrammatically in Figure 5.

PTM

Pulse-time modulation (PTM) is modulation in which values of the instantaneous samples of the modulating wave are used to vary the time of occurrence of some parameter of a pulse carrier. Pulse-duration modulation and pulse-position modulation are particular forms of pulse-time modulation.

Pulse-duration modulation (PDM), sometimes designated pulse-length modulation or pulse-width modulation, is modulation of a pulse carrier in which the value of each instantaneous sample of a modulating wave is used to vary the duration of a particular pulse. This is shown in Figure 5. The modulating wave may vary the time of occurrence of the leading edge, the trailing edge or both edges of the pulse.

In pulse-position modulation, (PPM) the value of each instantaneous sample of a modulating wave is used to vary the position in time of a pulse relative to its unmodulated position. An example of PPM is shown in Figure 5.

Like FM, PTM has the property that, by using extra bandwidth, some of the overall performance characteristics of a PTM system can be improved, provided that the peak interference is less than the peak signal. A feature of PPM is that, for fixed average power out of the transmitter, the peak power can be increased as the pulse duration is reduced. However, much of the advantage is lost where a large number of channels are considered.

PCM

Pulse-code modulation (PCM) is a relatively new innovation in pulse systems. As in the earlier pulse systems, each modulating wave is sampled periodically at a rate somewhat in excess of twice the highest frequency component in the modulating wave. Unlike the continuously variable samples used in PAM, PDM, and PPM, in PCM the samples are quantized into discrete steps. The individual steps may be alike or they may vary depending upon the characteristic properties of the modulating wave.

In addition, each quantized sample is assigned a particular code pattern, the code pattern assigned being uniquely related to the magnitude of the quantized sample. This gives rise to various possible patterns of coded pulses. For

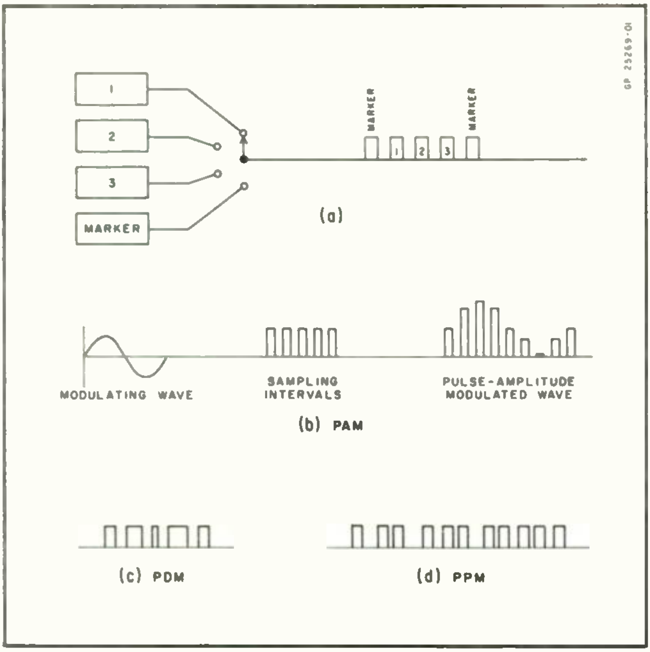

Fig. 5. Pulse Modulation. (a) Showing the position of the marker pulses used in time-division multiplex systems. (b) Pulse-Amplitude Modulation. (c) Pulse-Duration Modulation. (d) Pulse-Position Modulation.

example, if amplitude is the parameter quantized, there may be patterns of on or off pulses; or patterns of three-value code elements, namely, values of +S, O, and −S, as in the familiar case of submarine cable telegraphy; or, in general, code patterns which contain a number of code elements, and in which each code element will assume one of several distinct amplitude values. At the receiving end, each code pattern is identified, decoded, and used to produce a voltage proportional to the original quantized sample. From a succession of such samples, the original wave is approximated. By making each quantum step sufficiently small, theoretically the original wave may be approximated as closely as desired.

Pulse-code modulation has two outstanding properties: first, it affords marked freedom from noise and interference; and, second, it permits repeating the signals again and again without significant distortion. For example, consider the code patterns formed by on or off pulses. At each regenerative repeater, as long as each incoming pulse can be correctly identified in the presence of accumulated noise, interference, and distortion, a new and correct code pattern can be generated and started out afresh to the next repeater.

Conclusion

The inherent circuit capacity of a transmission medium can be filled using either frequency or time division techniques. The choice of multiplexing method and the type of modulation employed depends upon such factors as: compatibility with existing systems; loss over which the system may be effectively operated; bandwidth, signal-to-noise performance; interference-rejection capabilities; distortion characteristics; and, the required stability of the frequency generators. Each of the types of multiplexing and modulation discussed have inherent advantages and disadvantages, and in a number of cases any one of several methods might appear to have about equal capabilities for a given application. The final choice might then depend upon the relative complexity of the system.

In practice, toll carrier systems have been primarily made up of SSB-SC frequency-division multiplex systems. For these applications, this method is economically compatible and the total bandwidth required for the intelligence transmitted is held to a minimum in the present state of the art. Other types of modulation in frequency-division as well as time-division multiplex appear attractive for other carrier telephone applications.

A METHOD OF MEASURING DISTORTION

In Broad-Band Radio Systems

Unlike other types of interference commonly encountered in message circuits, intermodulation distortion is present only when the system is carrying traffic; and the character as well as magnitude of the interfering effects will vary depending upon the magnitude and frequency distribution of the signal(s) applied to the input terminals.

A number of methods have been developed for measuring intermodulation distortion. Many of these require the measurement of intermodulation products resulting from the application of one or more single frequency tones.

To completely determine the effect under different operating conditions, a large number of tests are required when tones are used. Even with numerous tests, it is difficult to correlate the data with interference that would result during actual operating conditions. Ideally, distortion should be measured under actual operating conditions. However, this is not usually practical, because of traffic conditions. In addition any measurement made while the system is operating cannot be readily duplicated at some other time.

Studies of the characteristics of speech and the habits of telephone users have shown that the complex wave input to a multi-channel radio system closely approximates that of random noise. The curve of Figure 1 shows a relationship between the speech habits and characteristics of a number of telephone users, and random noise power. In the figure, the total number of channels is related to the rms input power of random noise that would simulate the maximum talker load expected for all but the 1 percent busy hour condition. This maximum loading condition is a compromise between the engineering and economic factors that must be considered in good engineering design.

Intermodulation distortion can be measured by loading all but the equiva-

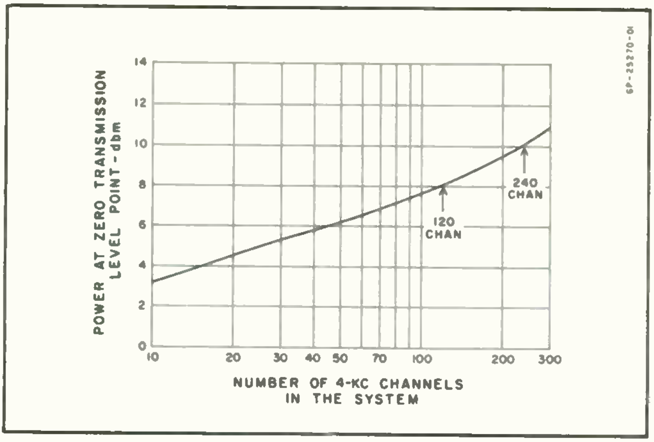

Fig. 1. Statistical loading of a broad-band system for all but the 1% busy-hour condition. Combined input power versus the number of channels for a radio system loaded with speech and -16 dbm signaling tones.

lent of 1 or 2 channels of the baseband by random noise. The manner in which this may be accomplished is best illustrated by an example. A typical test setup for Lenkurt Type 74A Radio is shown in block form in Figure 2. From the noise generator, broad-band random noise is applied to a Type 5203A Transmitting Distortion Test Set. Filters in the test set restrict the bandwidth to a range of 50 to 500 kc or 50 to 1100 kc depending upon whether 120 or 240 channels are being considered. Thus, the low and high end of the baseband are available for distortion measurements. For 120 channels of nominal 4-kc bandwidth, the input signal is +8 db, and for 240 channels it is +10 db (reference Figure 1), at the zero transmission level point.

At the receiving terminal, a Type 5204A Receiving Distortion Test Set is connected to the output of the radio receiver and a VTVM is bridged across the output terminal of the test set. First, the set is calibrated so that meter readings can be referred to reference noise level. A selector switch connects the proper filter into the metering circuit. For any one test two different filters are used, and both are outside the pass band of the transmitting filter. Each

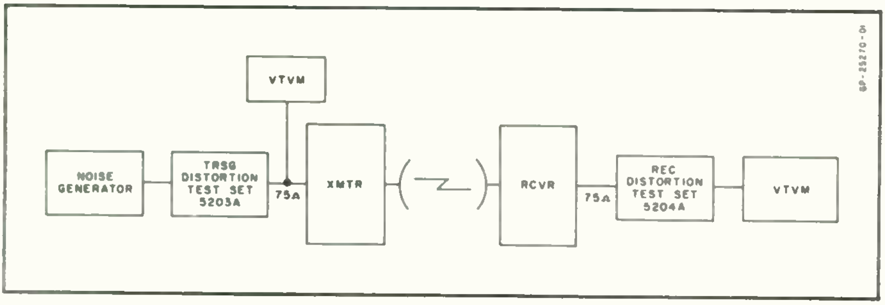

Fig. 2. Block diagram of a test setup used for the measurement of intermodulation distortion.

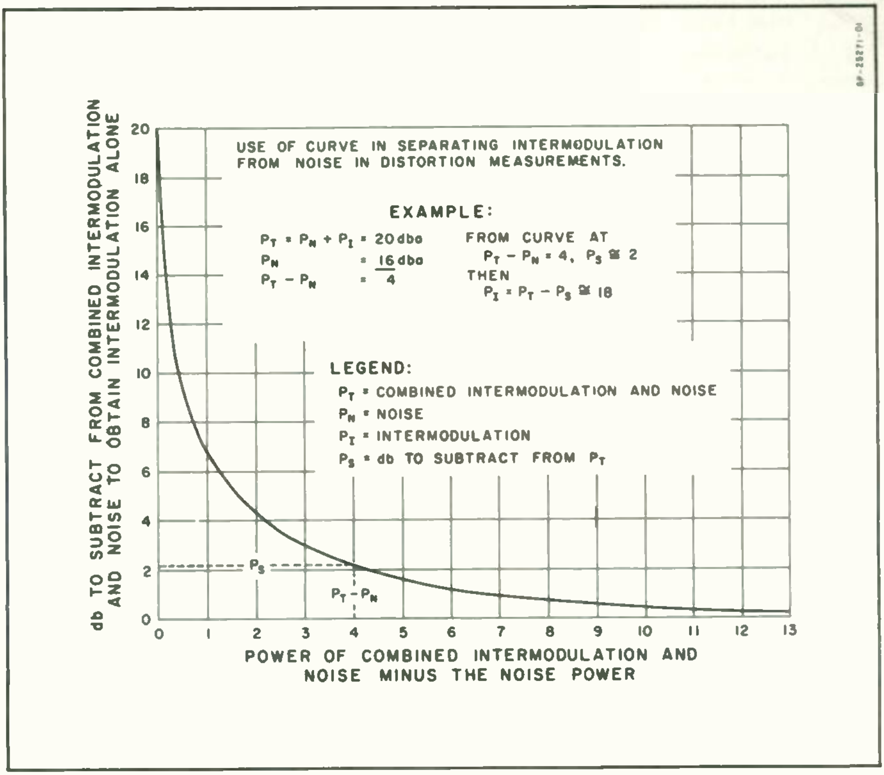

Fig. 3. A graphical means of determining the separate powers of two combined tones when the total power and one of the tone powers are known.

filter samples an effective 3-kc band of frequencies. Both noise and intermodulation distortion will be present.

By the calibration of the 5204A, the VTVM reads noise output in dbm with reference to zero level. For random noise, the reference noise level is –82 DBM. Therefore, subtraction of the meter reading from the reference level gives the interfering effect of the noise and intermodulation products in dba (F1A weighted) for a message channel. For example, assume that meter readings of –66 dbm at 26 kc, and –62 dbm at 1200 kc were obtained. The noise and intermodulation at 26 kc would be 16 dba (16 db above the reference level of –82 dbm), and at 1200 kc they would be 20 dba.

In some cases it may be desirable to separate the idle noise from the intermodulation noise to determine the extent of each. This may be done by removing the test set at the transmitting end and terminating the transmitter. Idle system noise can then be measured in the same manner as indicated for the combined idle noise and intermodulation products. The magnitude of intermodulation alone can then be determined by using the chart given in Figure 3.

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Bulletin 92A
Issue No. 3

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