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Required Signal-to-Noise Ratios for HF Communication Systems

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WESLEY M. BEERY

BOULDER, COLORADO
August 1969

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FOREWORD

The study described in this report was performed by the Institute for Telecommunication Sciences of the Environmental Science Services Administration, U.S. Department of Commerce, for and with the support of the U.S. Army Strategic Communications Command, Fort Huachuca, Arizona. The work was performed under Environmental Science Services Administration Project D51131145.

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

REQUIRED SIGNAL-TO-NOISE RATIOS FOR HF COMMUNICATION SYSTEMS

Hiroshi Akima, Gene G. Ax, and Wesley M. Beery

Values of required signal-to-noise ratios are estimated for the following HF communication systems: amplitude-modulation (AM) voice communication systems, noncoherent frequency-shift-keying (NCFSK) radioteletypewriter systems, composite voice and teletypewriter systems, aural-reception radiotelegraphy, and phototelegraphy (facsimile). Except for NCFSK systems, for which certain aspects of the basic performance had to be evaluated in the course of this study, values of required signal-to-noise ratios are estimated from published data in the open literature.

Key Words: Amplitude modulation, diversity reception, fading, frequency-shift-keying, HF communication system, radioteletypewriter, required signal-to-noise ratio, voice communication.

1. INTRODUCTION

1.1 Background

For monthly predictions of the lowest useful frequency (LUF), the Institute for Telecommunication Sciences (ITS) of the Environmental Science Services Administration (ESSA) currently uses the values of required signal-to-noise ratios given in Technical Report No. 4 issued by the U.S. Army Radio Propagation Agency (ARPA) (Silva, 1964). The International Radio Consultative Committee (CCIR) also has recommendations and reports (CCIR, 1964; 1967b, c, d) on similar subjects and gives values of required signal-to-noise ratios and fading allowances.

However, because there are some discrepancies between the ARPA and CCIR documents, we reevaluated and updated the values of required signal-to-noise ratios for various HF communication systems.

1.2 Objective and Scope

The objective of this study is to derive required signal-to-noise ratios for desired grades of service for various HF communication systems. The intention here is not to advance the state of the art for communications in an HF channel, but rather to derive best estimates of required signal-to-noise ratios for various existing systems and establish a documented source for reference purposes.

The required signal-to-noise ratio for any particular HF communication system is a function of many variables that cannot be predicted exactly, and we will therefore treat the required signal-to-noise ratio as a random variable and will obtain, whenever possible, estimates of its mean value and dispersion. The term "required signal-to-noise ratio" should be interpreted in this report as an estimate of the "mean value" of the required signal-to-noise ratios. An estimate of the dispersion, in terms of standard deviation, of the actual required signal-to-noise ratios about the mean value will be given.

Considered are:

(1) Radiotelephone (double-sideband and single-sideband amplitude modulation), radioteletypewriter (single channel, time-division multiplex, and frequency-division multiplex; noncoherent frequency-shift-keying), combined systems of voice and multiplexed teletypewriters, radiotelegraphy (Morse code, on-off keying, aural reception), and phototelegraphy or facsimile (frequency modulation of subcarrier).

(2) Stable (nonfading) conditions, fading conditions without diversity, and fading conditions with dual diversity. Three diversity combining methods (selection switching, equal gain, and maximal ratio) whenever applicable.

(3) Both white Gaussian noise and atmospheric noise. The amplitude probability distribution of atmospheric noise as described by CCIR (1964) is taken into account.

(4) For radiotelephony, required signal-to-noise ratios for both good commercial quality and just usable quality, sometimes called order-wire quality or operator-to-operator quality.

(5) For radioteletypewriter, required signal-to-noise ratios for probabilities of character error of 1 percent, 0.1 percent, and 0.01 percent. Both synchronous and start-stop systems. The maximum signalling rate in multiplexed teletypewriter channels is 1200 bit/sec in a 3-kHz bandwidth. Error control coding not considered.

For convenience of application of the results, required signal-to-noise ratio will be given in the form of signal-to-noise-density ratio in dB. This is defined as the ratio of unmodulated carrier power to average noise power in a 1-Hz radio-frequency (RF) bandwidth for double-sideband amplitude-modulation (DSB-AM) systems, and as the ratio of peak envelope power of the signal to average noise power in a 1-Hz RF bandwidth for other modulation systems. The terms carrier-to-noise ratio and carrier-to-noise-density ratio will sometimes be used in lieu of signal-to-noise ratio and signal-to-noise-density ratio, respectively, when we discuss a DSB-AM system. For a fading signal required signal-to-noise (or noise-density) ratio will be expressed in terms of median signal-to-noise (or noise-density) ratio defined as a ratio of median signal power to average noise power (or noise power density).

2. VOICE COMMUNICATION SYSTEMS

2.1 Modulation Techniques

Modulation techniques considered for voice communication over an HF channel are limited to double-sideband amplitude-modulation (DSB-AM), single-sideband amplitude-modulation (SSB-AM), and independent-sideband amplitude-modulation (ISB-AM). The nominal baseband bandwidth of a voice signal is 3 kHz. The RF bandwidth of an SSB-AM signal is also 3 kHz. A DSB-AM signal occupies an RF bandwidth of 6 kHz. An ISB-AM system accomodates up to four independent sidebands, each of which has a bandwidth of 3 kHz and can be either a voice, a facsimile, or a multiplexed digital signal.

A DSB-AM system has a threshold in its characteristic of signal-to-noise ratios, below which the signal-to-noise ratio at the demodulator output is not proportional to the carrier-to-noise ratio at the demodulator input. However, as will be shown later, the value of signal-to-noise ratio in which we are interested lies above the threshold, where, for a 100 percent modulated DSB-AM signal, the peak envelope power of the modulating signal at the demodulator output is equal to the carrier power at the demodulator input. On the other hand, the power spectral density of the noise at the demodulator output is twice the noise power spectral density at the demodulator input. Thus, the speech-to-noise-density ratio, defined as the ratio of the peak envelope power of the audio-frequency (AF) voice signal to the noise power spectral density in the baseband, is 3 dB lower than the carrier-to-noise-density ratio.

For an SSB-AM signal, the speech-to-noise-density ratio is equal to the RF signal-to-noise-density ratio. Therefore, the RF signal-to-noise-density ratio for an SSB-AM signal can be 3 dB lower than the carrier-to-noise-density ratio for a 100 percent modulated DSB-AM signal above the threshold to give an equal speech-to-noise-density ratio.

Considering noise power instead of noise power density, the carrier-to-noise ratio for a 100 percent modulated DSB-AM signal above threshold must be equal to the signal-to-noise ratio for an SSB-AM signal to give an equal speech-to-noise ratio; where the carrier-to-noise ratio for a DSB-AM signal is the ratio of carrier power to average noise power in a 6-kHz RF bandwidth, the signal-to-noise ratio for an SSB-AM signal is the ratio of peak envelope power of the signal to average noise power in a 3-kHz RF bandwidth, and the speech-to-noise ratio is the ratio of peak envelope power of the AF voice signal to average noise power in a 3-kHz AF bandwidth.

The above relation provides us with a means for estimating the required signal-to-noise ratio for an SSB-AM system from test results made on a DSB-AM system, and vice versa.

In the preceding paragraphs, complete carrier suppression has been assumed for SSB-AM signals. From the engineering standpoint, CCIR (1967a) defines two types of SSB-AM signals: one with a reduced carrier and the other with a suppressed carrier. The reduced carrier is defined as a "carrier emitted at a power level between 6 dB and 32 dB below the peak envelope power and preferably between 16 dB and 26 dB below the peak envelope power." The suppressed carrier is defined as a "carrier restricted to a power level more than 32 dB below the peak envelope power and preferably 40 dB or more below the peak envelope power." The RF signal-to-noise-density ratio for an actual SSB-AM signal must be higher than that for a conceptual SSB-AM signal without carrier by a correction factor that depends on the carrier reduction. For SSB-AM signals with carriers emitted at power levels of 6 dB, 16 dB, 20 dB, 26 dB, 32 dB, and 40 dB below the peak envelope power, the correction factors are equal to 6.0 dB, 1.5 dB, 0.9 dB, 0.4 dB, 0.2 dB, and 0.1 dB, respectively. For practical purposes, the correction factor for an SSB-AM signal with a suppressed carrier as defined by the CCIR is negligible. Therefore, for simplicity the term "SSB-AM signal" will be used in this report to indicate an SSB-AM signal with a suppressed carrier, unless otherwise noted.

Another important point is that the channel, which here is taken to include the RF equipment, is peak-limited as far as transmission of speech is concerned. No matter what modulation technique is used, the instantaneous peak voltage, not the average power, of the voice signal is limited by the channel. On the other hand, as will be shown later, the intelligibility of a voice signal is essentially insensitive to peak clipping of the signal in a certain range of clipping levels. In this range the intelligibility of a voice signal primarily depends on the ratio of average power, not peak power, of the voice signal to average noise power. These facts create a difficult technical problem in setting the level for voice signals, which may be one of the most important reasons for the strongly divergent intelligibility test results.

2.2 Expression of Voice Quality

It is not difficult for most listeners to subjectively classify voice quality into the following five grades: excellent, good, fair, poor, and bad (hopeless). But because the criterion for this assessment depends on the listeners, only a statistically processed grade derived from the assessed grades by a number of listeners has a useful meaning.

Voice quality can also be scored by various hearing tests, such as nonsense syllable articulation tests (French and Steinberg, 1947), phonetically balanced (PB) word articulation tests (Egan, 1944), rhyme tests (Fairbanks, 1958), modified rhyme test (House et al., 1965), and sentence intelligibility tests (Fletcher, 1953). Each of these tests has its own advantages and disadvantages.

Relation between PB word articulation and sentence intelligibility is shown in figure 1. Of the two curves, one is taken from Licklider and Goffard (1947), the other is derived from the relations between articulation index and various measures of speech intelligibility (see fig. 5) given by Kryter (1962a). That the two curves are significantly different can be appreciated if we recognize that, as we shall see, a difference of 20 percent in PB word articulation corresponds approximately to a 5-dB difference in required signal-to-noise ratio. The difference in these two curves is only an example of the wide divergence of existing data on required signal-to-noise ratios for voice communication.

Hirsh et al. (1954) obtained articulation scores for nonsense syllables and for monosyllabic, disyllabic, and polysyllabic words as a function of the cutoff frequency of low-pass and high-pass filters, and also as a function of signal-to-noise ratio at different noise levels. The results indicate that the relation between the intelligibility of each word type and of nonsense syllables is not the same when the system is impaired by filtering as when it is impaired by noise.

In an attempt to eliminate speech-intelligibility testing, which is expensive and time-consuming, a procedure was developed for calculating from physical and acoustical measurements made on a communication system a measure that is indicative of the intelligibility scores that would be obtained for that system under actual test conditions (Kryter, 1962a, b). This measure is called the "articulation index" and is described in section 2.4.

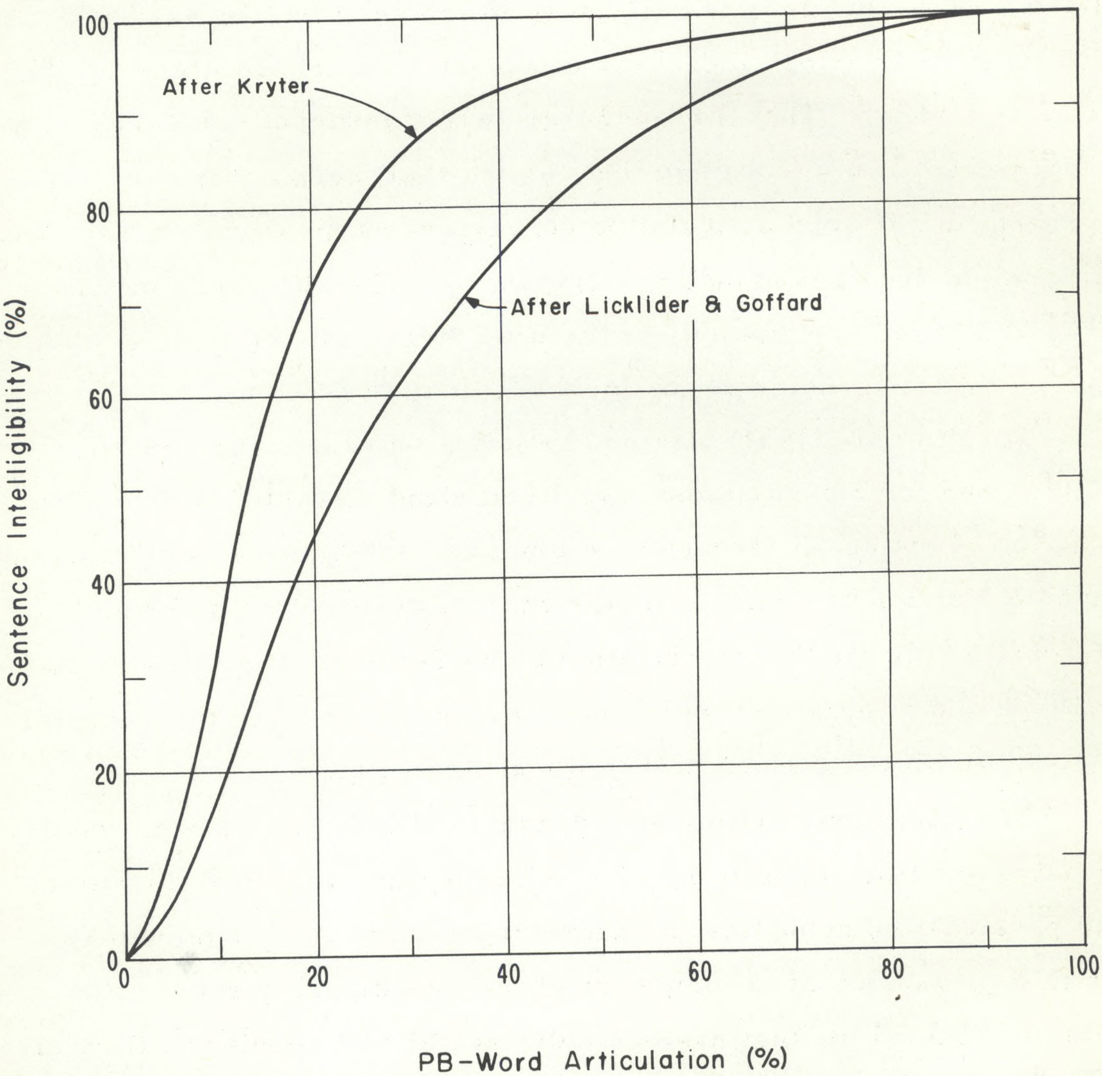

Figure 1. Relation between PB word articulation and sentence intelligibility. (After Licklider and Goffard, 1947; Kryter, 1962a.)

2.3 Articulation Test Results

Many tests conducted to determine the relation between signal-to-noise ratio and word articulation have been reported. Because these tests were not necessarily based on a 3-kHz bandwidth, we need a conversion relationship between baseband bandwidth and articulation to make use of the test results. Figure 2 shows the relation between carrier-to-noise-density ratio and PB word articulation for DSB-AM signals determined with various RF bandwidths by Cunningham et al. (1947). It indicates that, for the range of articulation of 40 to 60 percent, required signal-to-noise-density ratio does not change very much with the RF bandwidth. For example, required carrier-to-noise-density ratio for 60 percent articulation with a 9.6-kHz bandwidth differs by less than 1 dB from the required carrier-to-noise-density ratio for the same articulation with a 5.2-kHz bandwidth.

Figure 2 also indicates that the wider the RF bandwidth the more rapidly the articulation decreases with a decrease of the carrier-to-noise-density ratio. This can be interpreted as the effect of the threshold in the characteristics of signal-to-noise-density ratio of DSB-AM systems. For example, at a carrier-to-noise-density ratio of 45 dB, the RF carrier-to-noise ratios at the demodulator input are 8, 5, 2, and -2 dB, respectively, for RF bandwidths of 5.2, 9.6, 21, and 52 kHz. The first, 8 dB, is about at the threshold value, i.e., the lower end of the linear range of the characteristic; the others are below the threshold. Therefore, we may expect that, if the same test were made on SSB-AM signals, the effect of bandwidth would be less than that shown in this figure. The articulation also seems to depend primarily on the speech-to-noise-density ratio, and not on the speech-to-noise ratio. This conclusion is in agreement with the concept of the articulation index, to be discussed in the next section.

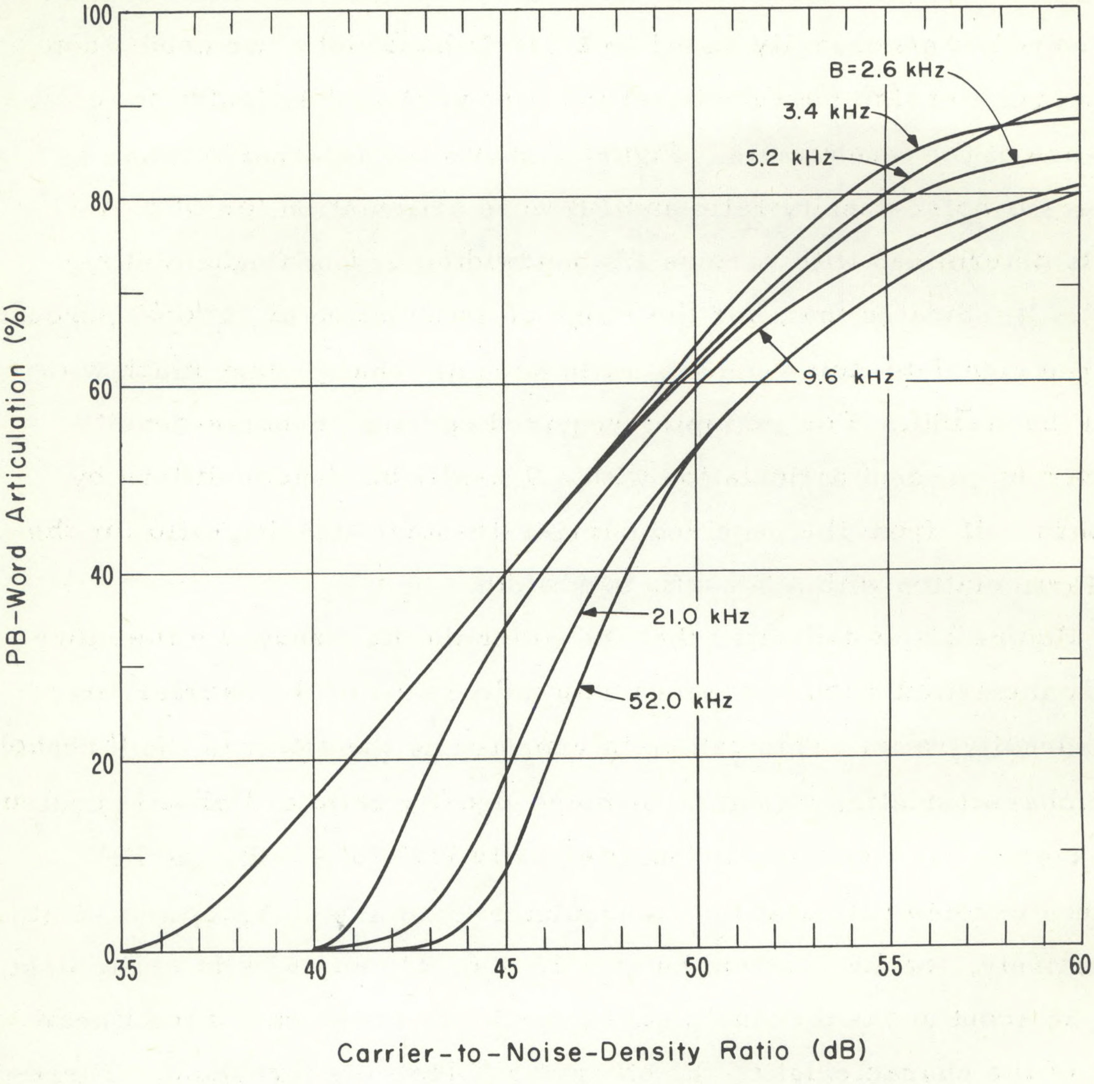

Figure 2. Relation between carrier-to-noise-density ratio and PB word articulation for DSB-AM signals and white Gaussian noise for different values of the IF bandwidth B. (Carrier-to-noise-density ratio is the ratio of carrier power to average noise power contained in a 1-Hz bandwidth.) (After Cunningham et al., 1947.)

Many investigators (Licklider, 1946; Kryter et al., 1947; Licklider and Pollack, 1948; Pollack and Pickett, 1959; Ewing and Huddy, 1966) have reported that peak clipping of a voice signal does not seriously degrade the signal's intelligibility. Since our communication channel is peak-limited, peak clipping and amplification improve the intelligibility with equal speech-to-noise ratio (the ratio between the peak AF signal power and the noise power). As an example, from the test results in figure 3 (taken from Ewing and Huddy, 1966), we see that the curve for 12-dB RF clipping lies about 12 dB left of the curve for no clipping. This means that a difference of 12 dB in the level setting appears directly as a difference of the same amount in the required signal-to-noise ratio. Figure 3 also indicates that AF clipping results in less improvement than RF clipping; because more harmonic distortion terms due to peak clipping fall in the baseband, the voice quality is degraded more severely in AF than in RF clipping.

Relations between carrier-to-noise-density ratio and PB word articulation for DSB-AM systems taken from four sources (Cunningham et al., 1947; Licklider and Goffard, 1947; Craiglow et al., 1961; Ewing and Huddy, 1966) are shown in figure 4. In their tests, Cunningham et al. (1947) and Licklider and Goffard (1947) adjusted the speech amplifier to provide 100-percent modulation on the average instantaneous peaks of the speech wave, monitoring the speech wave on an oscilloscope. For the other two tests cited, the criteria of level setting are not known. As figure 4 shows, the articulation test results diverge widely, and the values of required carrier-to-noise-density ratio for a particular value of articulation taken from the data are distributed in a range as wide as 12 dB.

There are several possible reasons for the wide divergence among the articulation test results. Skill of talkers and listeners is one factor, but, if a well-trained team of listeners is used, the articulation score

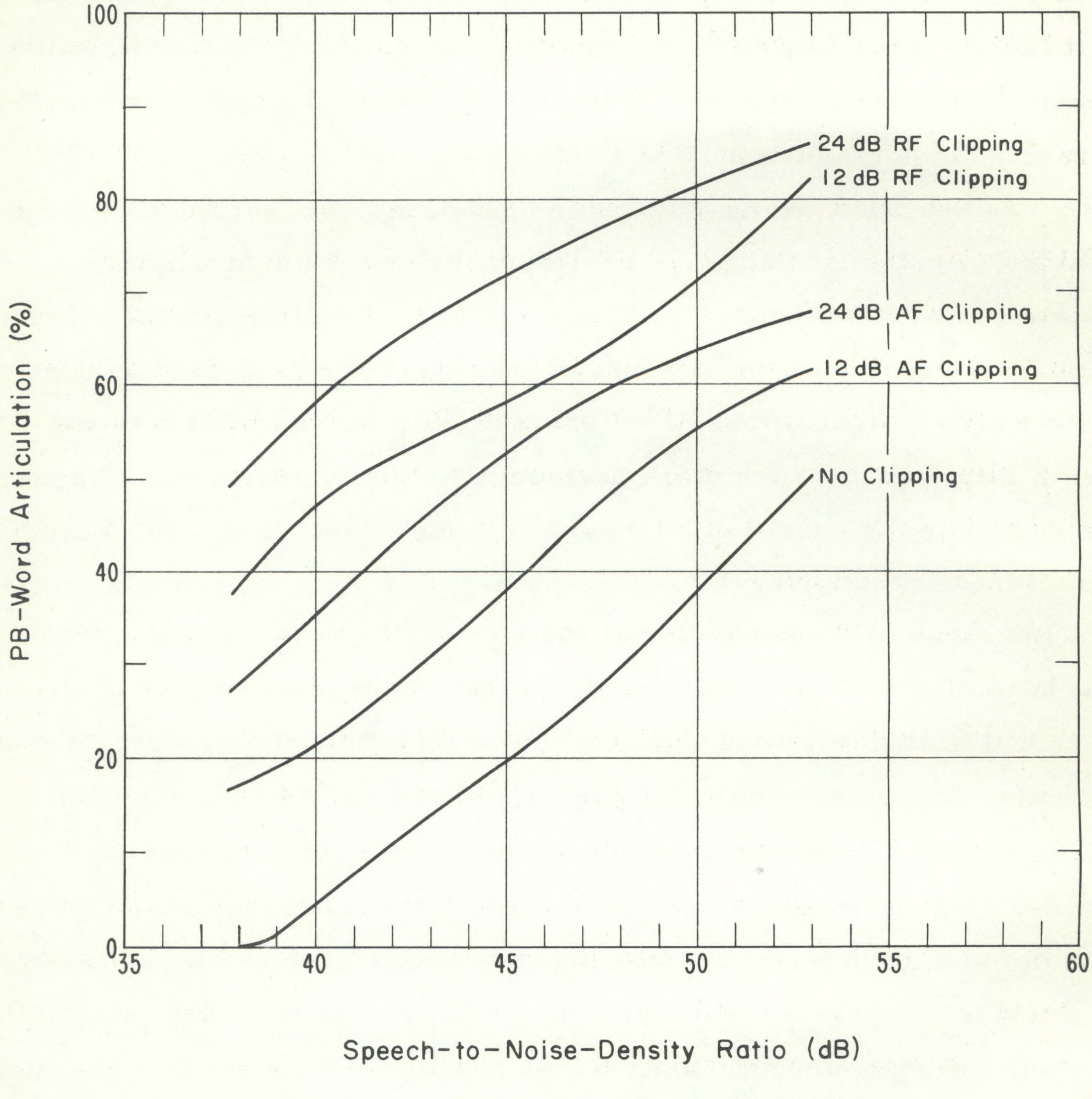

Figure 3. Relation between speech-to-noise-density ratio and PB word articulation with RF peak clipping, with AF peak clipping, and without peak clipping. (Speech-to-noise-density ratio is the ratio of the peak envelope power of the voice signal to average noise power contained in a 1-Hz bandwidth.) (After Ewing and Huddy, 1966.)

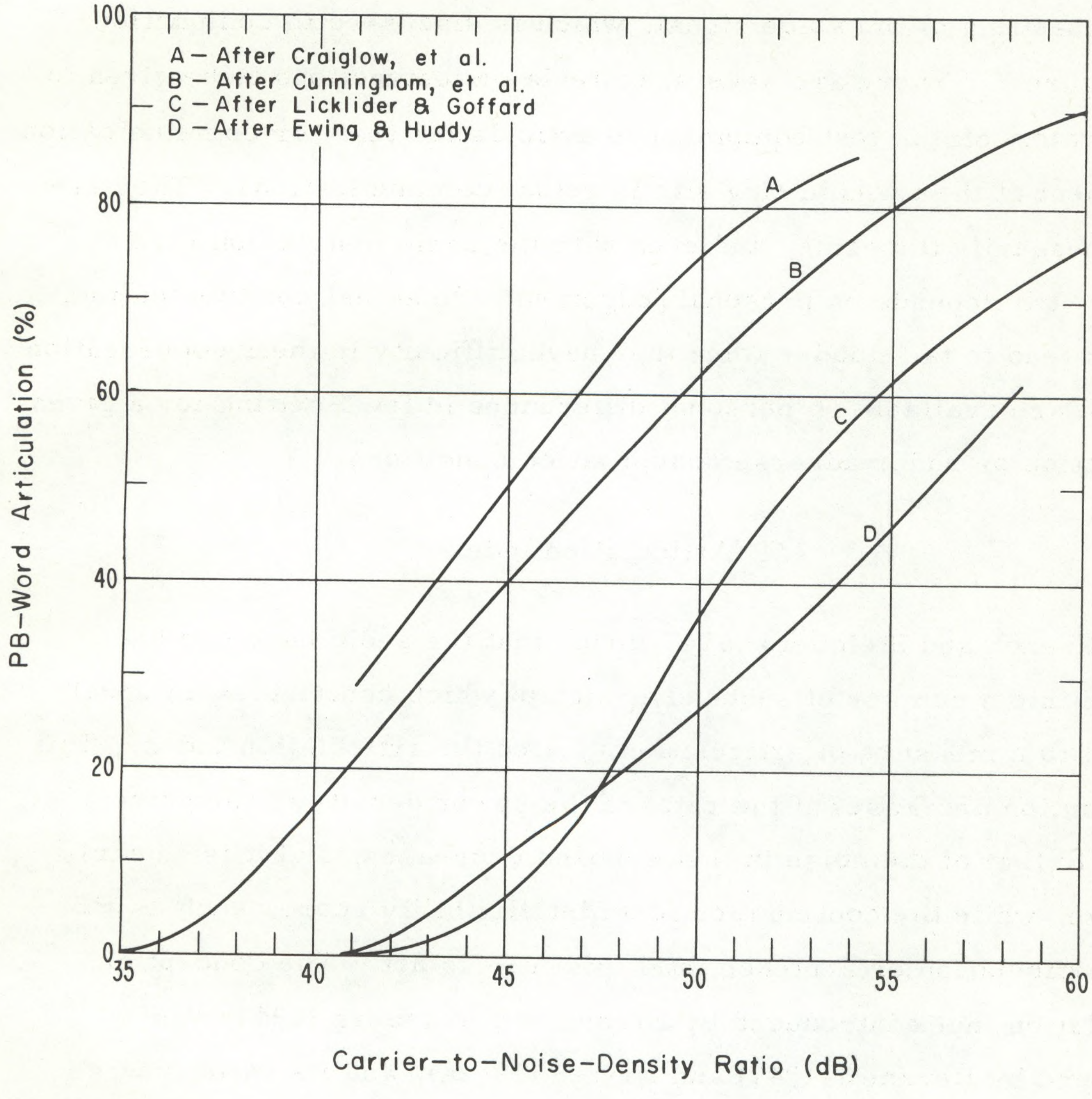

Figure 4. Relation between carrier-to-noise-density ratio and PB word articulation for DSB-AM signals and white Gaussian noise by different investigators. (Carrier-to-noise-density ratio is the ratio of carrier power to average noise power contained in a 1-Hz bandwidth.) (After Cunningham et al., 1947; Licklider and Goffard, 1947; Craiglow et al., 1961; Ewing and Huddy, 1966.)

will be very precise and reliable (Stuckey, 1963). Environmental conditions can also have an effect, but are very difficult to specify. Another factor, very important but given little attention, is the problem of level setting of the voice signal, which is discussed in conjunction with figure 3. There are several criteria or instructions to be given to an operator of the test equipment in articulation tests or communication equipment at the transmitting site in actual communications. They are not necessarily the same, and even with the same instruction level setting still depends on personal judgement. In actual communication, talkers tend to talk louder when they have difficulty in their conversation. No data are available on personal differences in level setting for a given instruction or under adverse conversation conditions.

2.4 Articulation Index

French and Steinberg (1947) found that the audio band can be divided into a number of subbands, each of which contributes an equal amount to a measure of articulation, called the articulation index. This contribution decreases if the ratio of the power density of the voice signal to that of the noise in that subband decreases, and it is linearly additive, while the contribution to an intelligibility score, such as PB word articulation or sentence intelligibility, is not. The concept of articulation index introduced by French and Steinberg (1947) was developed by Beranek (1947) and Kryter (1962a), and its validity was demonstrated by Kryter (1962b).

Approximate relations between the articulation index and various measures of speech intelligibility are given in figure 5. These relations are approximate in the sense that they depend upon type of material and skill of talkers and listeners.

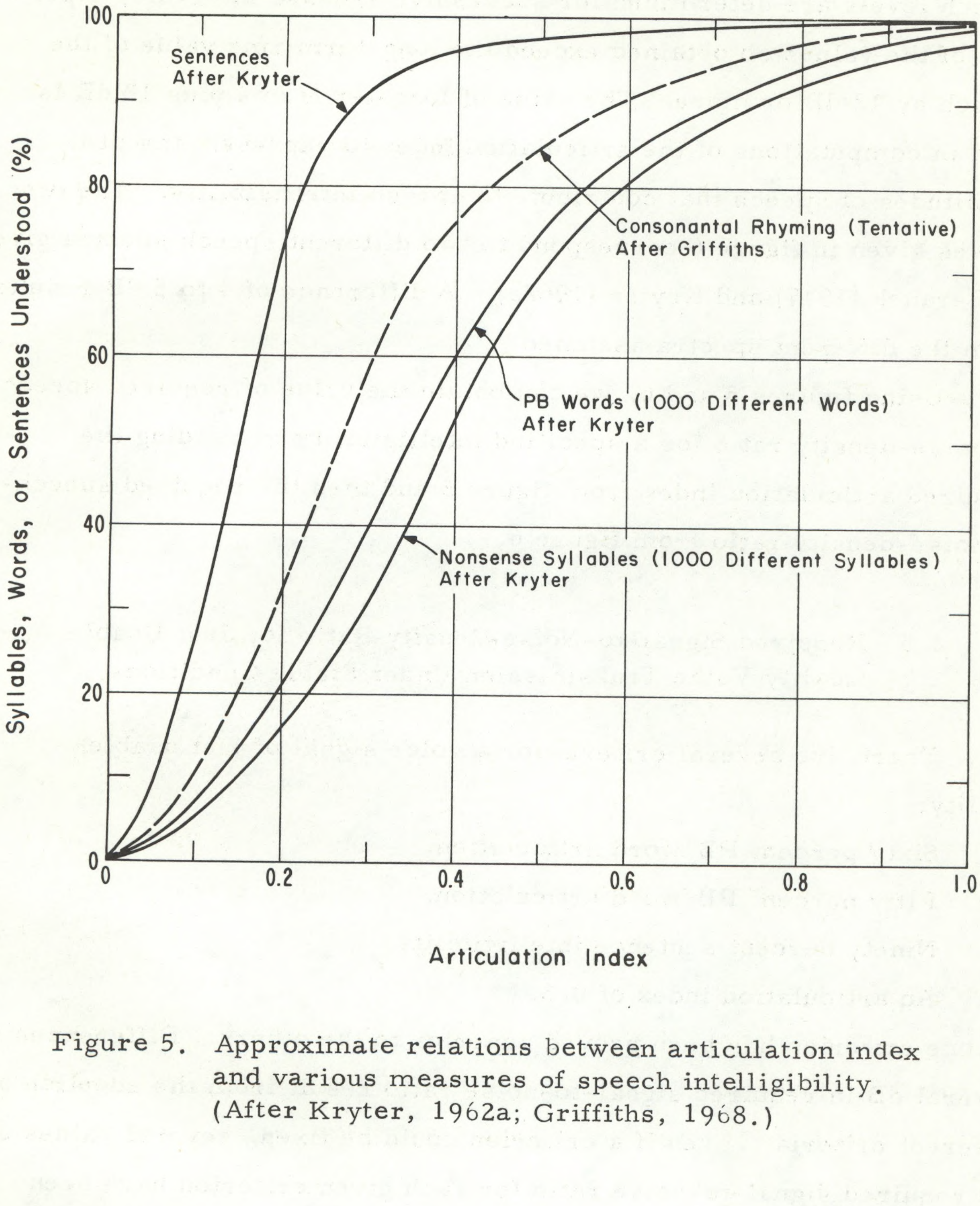

Figure 5. Approximate relations between articulation index and various measures of speech intelligibility. (After Kryter, 1962a; Griffiths, 1968.)

Relation between speech-to-noise-density ratio and articulation index is computed according to the method suggested by Kryter (1962a) and is shown in figure 6. According to Kryter, if the rms values of the speech levels are determined for successive 1/8-sec intervals, 1 percent of the values so obtained exceed the long-term rms value of the speech by 12 dB or more. The value of long-term rms plus 12 dB is used in computations of the articulation index to represent the peak amplitudes of speech that contribute to speech intelligibility. The two curves given in figure 6 correspond to two different speech spectra given by Beranek (1947) and Kryter (1962a). A difference of 4 to 5 dB results from the different spectra assumed.

Using figures 5 and 6, we can obtain the value of required speech-to-noise-density ratio for a specified intelligibility by reading the required articulation index from figure 5 and then the required speech-to-noise-density ratio from figure 6.

2.5 Required Signal-to-Noise-Density Ratio for Just Usable Quality Voice Transmission Under Stable Conditions

There are several criteria for a voice signal of just usable quality:

Sixty percent PB word articulation.

Fifty percent PB word articulation.

Ninety percent sentence intelligibility.

An articulation index of 0.3.

No one criterion has been proved superior to the others. Differences of several dB in required signal-to-noise ratio result from the adoption of different criteria. Even if a criterion could be fixed, several values of the required signal-to-noise ratio for each given criterion have been reported by different investigators.

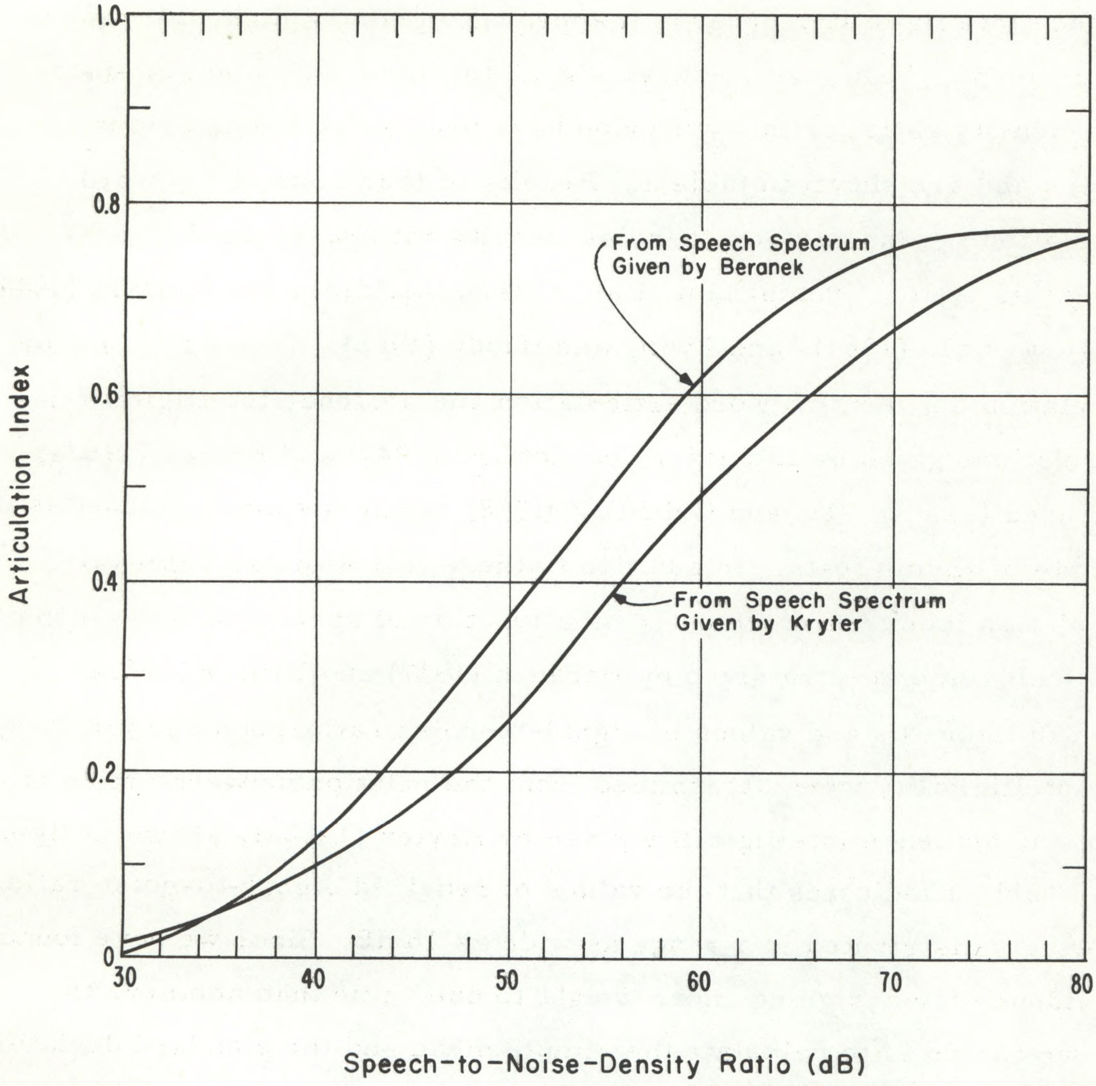

Figure 6. Relation between speech-to-noise-density ratio and articulation index, based on voice spectra given by Beranek (1947) and Kryter (1962a). (Speech-to-noise-density ratio is the ratio of the peak envelope power of the voice signal to average noise power contained in a 1-Hz bandwidth.)

In view of the above, we can only try to arrive at a reasonable estimate of the required signal-to-noise ratio for a voice signal of just usable quality, and to do so we have adopted the criterion of 90-percent sentence intelligibility, because it appears to give the highest measure of agreement. Values of required signal-to-noise ratio and signal-to-noise-density ratio for this criterion have been taken from various sources and are shown in table 1. Results of four tests of PB word articulation versus carrier-to-noise-density ratio were used in preparing this table: Cunningham et al. (1947), Licklider and Goffard (1947), Craiglow et al. (1961), and Ewing and Huddy (1966). (See fig. 4.) For the relation between PB word articulation and sentence intelligibility, two relations given by Licklider and Goffard (1947) and Kryter (1962a) were used (see fig. 1), and Griffiths' (1968) result has been included as an example of rhyme tests. In addition to these test results, values of articulation index were computed as a function of speech-to-noise-density ratio with voice spectra given by Beranek (1947) and Kryter (1962a), shown in figure 6, and values of signal-to-noise ratio required for 90-percent intelligibility were determined from the relation between articulation index and sentence intelligibility given by Kryter (1962a), shown in figure 5.

Table 1 indicates that the values of required signal-to-noise ratio are widely distributed in a range as wide as 16 dB. Since we have found no evidence for assigning more weight to one value than another, the best we can do is to calculate the simple mean and the standard deviation for each column of the table. The results are given at the bottom of the table. We suggest that the values of 50 dB and 47 dB be used as the values of required signal-to-noise-density ratio for voice signal of just usable quality for DSB-AM and SSB-AM systems, respectively. If the uncertainty associated with the adoption of the criterion for just usable voice quality is also taken into account, the estimated dispersion associated with these values of required signal-to-noise-density ratio is approximately 5 dB in terms of standard deviation.

Table 1. Values of Required Signal-to-Noise Ratio for Voice Communication of 90-Percent Sentence Intelligibility Taken From Various Sources

Required Signal-to-Noise Ratio in dB				Data Source References		
DSB-AM		SSB-AM		Articulation test by	Conversion from word articulation to sentence intelligibility by	Articulation index based on voice spectrum given by
Carrier-to-noise (6 kHz) ratio	Carrier-to-noise-density ratio	PEP-to-noise (3 kHz) ratio	PEP-to-noise-density ratio			
11	49	11	46	Cunningham et al. (1947)		---
17	55	17	52	Licklider & Goffard (1947)	Licklider & Goffard (1947)	---
9	47	11	46	Craiglow et al. (1961)		---
20	58	20	55	Ewing & Huddy (1966)		---
6	44	6	41	Cunningham et al. (1947)		---
11	49	11	46	Licklider & Goffard (1947)	Kryter (1962a)	---
4	42	6	41	Craiglow et al. (1961)		---
14	52	14	49	Ewing and Huddy (1966)		---
10	48	10	45	Griffiths (1968)	Griffiths (1968)	---
12	50	12	47	---	---	Beranek (1947)
16	54	16	51	---	---	Kryter (1962a)
11.8	49.8	12.0	47.0	Mean value		
4.5	4.5	4.4	4.4	Standard deviation		

PEP stands for peak envelope power.

The preceding discussion has dealt with the effects of Gaussian noise. On HF channels, however, the noise is mostly atmospheric, impulsive in its waveform. Tests were carried out by Licklider and Goffard (1947) with impulsive noise consisting of irregularly spaced pulses and by Daspit and Henderson (1968) with one sample of recorded atmospheric noise. These tests, with DSB-AM signals, indicate that, if no noise limiter is used, the required carrier-to-noise ratio can be 5 to 10 dB lower than that required for Gaussian noise. The results also indicate that the required carrier-to-noise ratio can be reduced markedly if a noise limiter is used. The resulting improvement factor is a function of average pulse-repetition frequency, irregularity of pulse spacing, receiver IF bandwidth, limiting level of the noise limiter, required PB word articulation, and other parameters. Since insufficient data are available that relate the improvement factor to the amplitude probability distribution of atmospheric noise described by CCIR (1964), it is recommended that the values of required signal-to-noise-density ratios for Gaussian noise suggested in the preceding paragraph be used until such data become available.

The values of required signal-to-noise-density ratios determined in this section are pessimistic, because neither possible improvement that may result from use of a noise limiter against impulsive noise nor possible improvement by peak clipping in the transmitter, described in section 2.3, is taken into account. Note that the values correspond to a level setting of the voice signal at the transmitter whereby no significant peak clipping occurs.

2.6 Fading Allowances for Just Usable Quality Voice Transmission

The fading allowance is defined here as the difference, in dB, between the median signal-to-noise ratio for a fading signal during a short time in which the statistics of the signal-to-noise ratio may be considered stationary, and the signal-to-noise ratio for a steady signal, when equal quality of transmission is obtained in both cases. It is not the same as the fading allowance defined by CCIR (1967c). It is convenient to define system performance statistically in terms of three parameters: grade of service, time availability, and service probability (Barsis et al., 1961; CCIR, 1964). The fading allowance in CCIR (1967c), however, is the sum of two factors: the fading safety factor, which is related to the grade of service, and the intensity fluctuation factor, which is the protection factor for a time availability of 90 percent. Thus, the CCIR recommendation and concepts are not consistent, and since the concepts (CCIR, 1964) are more generally accepted, we do not use the definition of fading allowance given by CCIR (1967c).

When a radio wave modulated by a voice signal is fading at a very high rate, on the order of several hertz or higher, or when the fading is frequency selective, i.e., when different portions of the spectrum of the signal are fading differently, the voice signal suffers severe degradation that cannot be compensated for by increasing the signal-to-noise ratio. Fading allowance cannot be defined in such cases.

When, on the other hand, the fading is slow and flat (not frequency-selective) its effect is merely the intermittent attenuation of the voice signal. Therefore, the relation between median signal-to-noise ratio and word articulation for a fading signal can be determined from that for a steady signal by computing weighted means, with the probability density function of the fading signal used as a weighting function. As an example, we selected the relation between carrier-to-noise-density ratio and PB word articulation for the IF bandwidth of 5.2 kHz by Cunningham et al. (1947) as typical for the steady signal and, assuming Rayleigh fading computed the relation for no diversity and dual diversity with three types of combining techniques. The results are shown in figure 7, where the probability density functions of diversity combiner output signals given by Altman and Sichak (1956) are used. This figure indicates that, in the case of no diversity, the fading allowance for a Rayleigh fading voice signal is about 1 dB for just usable quality, i.e., PB word articulation of 30 to 60 percent.

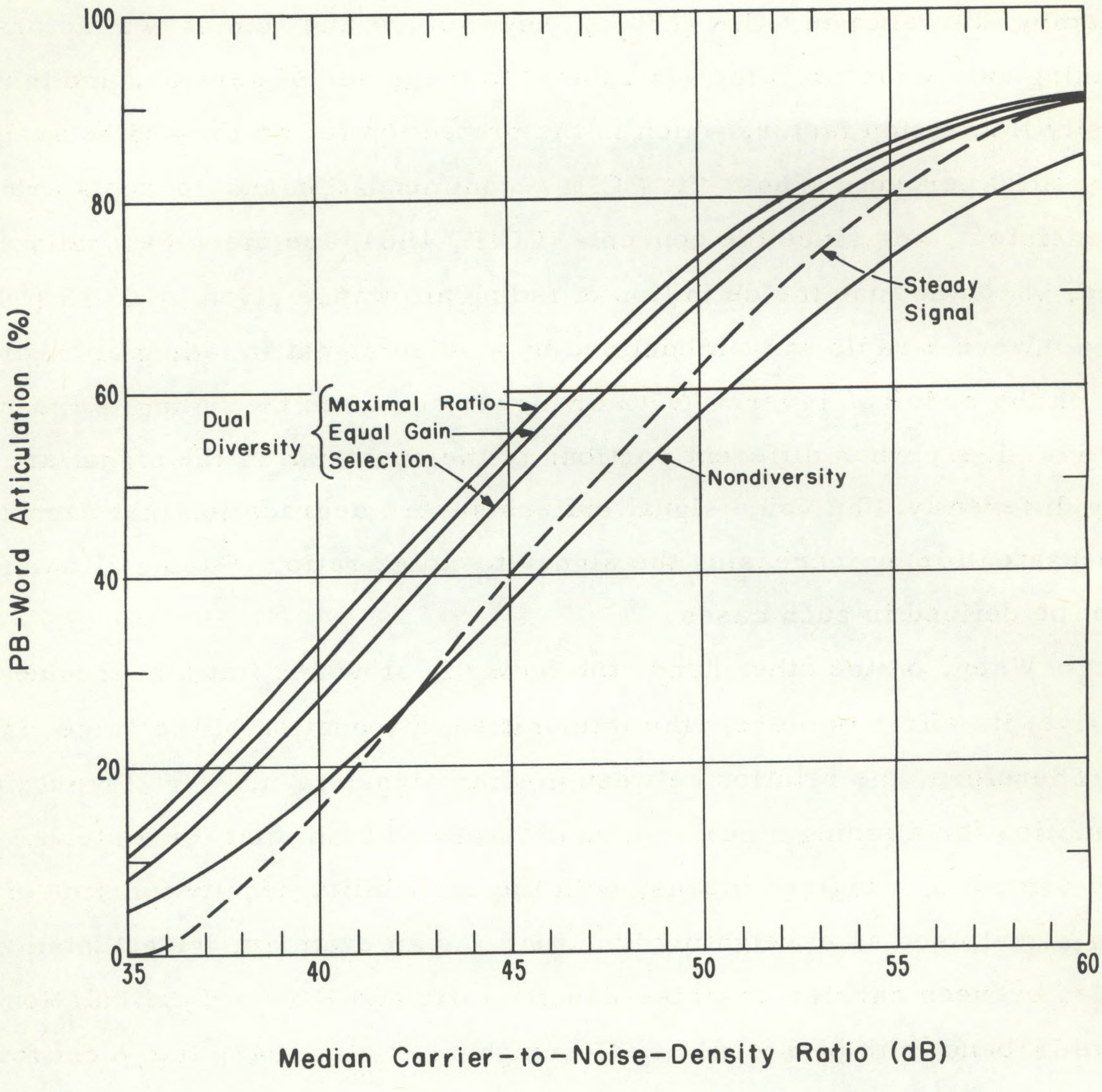

Figure 7. Relations between median carrier-to-noise-density ratio and average PB word articulation with and without dual diversity under slow Rayleigh fading conditions, and comparison with the same relation for a steady signal. The curve for a steady signal is after Cunningham et al. (1947). (Median carrier-to-noise-density ratio is the ratio of median carrier power to average noise power contained in a 1-Hz bandwidth.)

There are some questions concerning the applicability of certain diversity combining techniques to voice communications. Although the effects of three types of combining techniques are shown in figure 7, only selection diversity combining is practical in simple diversity systems because of distortion problems that may arise with equal-gain and maximal-ratio diversity combining. This figure indicates that the fading allowance for the case of Rayleigh fading is -2 dB when dual diversity with selection switching is used, which means that the median carrier-to-noise-density ratio for Rayleigh fading signals can be 2 dB lower than for nonfading signals, for an equal articulation score.

Our results for log-normal-fading signals having fading ranges (ratio of upper and lower deciles) of 10 to 15 dB for nondiversity and dual selection-switching diversity indicate that these curves lie within 1 dB of their respective curves for Rayleigh-fading signals.

For voice communications, diversity reception is effective only for flat fading signals, but, for flat fading received signals from the antennas separated by, say, 5 to 10 wavelengths, are generally still highly correlated. CCIR (1967f) describes the improvement achieved by widely spaced diversity receiving antennas in which the two receivers are located about 135 km apart, but makes no mention of efforts to determine the minimum distance at which the correlation between the fading signals received at the two antennas decreases sufficiently to permit effective diversity operation.

A different diversity technique based on audio frequency band-splitting and combining methods exists that is designed to be effective for selective fading of the signals (CCIR, 1967f), but no data are available on the amount of improvement achieved by this technique over the non-diversity case.

2.7 Required Signal-to-Noise-Density Ratio for Good Commercial Quality Voice Transmission

Our study has not revealed any evidence suggesting the need for revising the values of required signal-to-noise ratios for voice communication of good commercial quality recommended by CCIR (1967b) and adopted by ARPA (Silva, 1964). On the assumption of a 10-dB improvement achieved with noise reducers, CCIR gives values of 35 dB and 26 dB as the required ratios of peak envelope power of the signal to average power of the noise in a 6-kHz RF band for DSB-AM and SSB-AM systems, respectively. These values correspond to 67 dB and 64 dB, respectively, for the required signal-to-noise-density ratios for DSB-AM and SSB-AM systems. Note that, for DSB-AM systems, the CCIR recommendation is based on the peak envelope power of the signal, while in this report signal power is defined as the unmodulated carrier power of the signal when determining signal-to-noise-density ratios.

For slow, flat fading of the signal, good commercial quality may be defined as meaning that the actual signal-to-noise ratio exceeds the required signal-to-noise ratio for a steady signal for a specified percentage of the time. The value of 90 percent of the time is commonly used for voice communication of good commercial quality (CCIR, 1967c; Silva, 1964) and retention of this value is recommended. In this case, the fading allowance is merely the difference, in dB, between the median level and the lower decile level of the fading signal. For slow, flat, Rayleigh fading, the fading allowances are 8.2 dB and 2.6 dB, for no diversity and dual selection diversity, respectively (Altman and Sichak, 1956).

2.8 Multiplexing

When two, three, and four voice signals are multiplexed and transmitted together as a composite ISB-AM transmission, the peak envelope power is higher than that of a single-channel SSB-AM transmission by 1.5 dB, 2.3 dB, and 3.2 dB, respectively (Morrow et al., 1956). Therefore, the required signal-to-noise-density ratios for multiple-channel ISB-AM transmissions are higher than that for a single-channel SSB-AM transmission by the same amounts.

2.9 Summary for Voice Communication Systems

Our findings for voice communication systems are as follows:

(1) Under stable conditions the required signal-to-noise-density ratios for voice communication of just usable quality for DSB-AM and SSB-AM systems are estimated to be 50 dB and 47 dB, respectively. The estimated standard deviation of the required signal-to-noise-density ratio around these values is 5 dB.

(2) Allowances for slow Rayleigh fading for voice communication of just usable quality are estimated to be 1 dB and -2 dB for no diversity and dual diversity (selection-switching), respectively.

(3) Under stable conditions, the required signal-to-noise-density ratios for voice communication of good commercial quality are 67 dB and 64 dB for DSB-AM and SSB-AM systems, respectively.

(4) Allowances for slow Rayleigh fading for voice communication of good commercial quality are 8.2 dB and 2.6 dB for no diversity and dual diversity (selection-switching), respectively.

(5) The required signal-to-noise-density ratios for two-, three-, and four-channel ISB-AM signals should be higher than for a single-channel SSB-AM signal of equal quality by 1.5 dB, 2.3 dB, and 3.2 dB, respectively.

(6) Recommended values of required signal-to-noise-density ratios for voice communication systems under various conditions are summarized in table 2.

Table 2. Required Signal-to-Noise-Density Ratios for Various Voice Communication Systems

Type of Service		Required Signal-to-Noise-Density Ratio (dB)					
Emission designation	Description	Just usable quality			Good commercial quality		
		Stable condition	Fading condition		Stable condition	Fading condition	
			No diversity	Dual diversity		No diversity	Dual diversity
6A3	DSB-AM	50	51	48	67	75	70
3A3A	SSB-AM reduced carrier*	48	49	46	65	73	68
3A3J	SSB-AM suppressed carrier	47	48	45	64	72	67
6A3B	ISB-AM two voice channels	49	50	47	66	74	69
9A3B	ISB-AM three voice channels	49	50	47	66	74	69
12A3B	ISB-AM four voice channels	50	51	48	67	75	70

Signal-to-noise-density ratio is the ratio of carrier power to average noise power contained in a 1-Hz bandwidth for 6A3 emissions and is the ratio of signal peak envelope power to average noise power in a 1-Hz bandwidth for other types of emissions. For fading conditions carrier and signal peak envelope powers should be interpreted as median values.

*Carrier emitted at a level 20 dB below the peak envelope power.

3. DIGITAL COMMUNICATION SYSTEMS

3.1 Modulation Techniques

Modulation techniques to be considered for digital communications are limited to noncoherent frequency-shift-keying (NCFSK) systems. This type of system is characterized by its modulation rate and the frequency shift used. The modulation rate is defined as the reciprocal of the signalling unit interval measured in seconds and is expressed in bauds (CCITT,1966). The frequency shift is the difference between the frequencies corresponding to the "mark" and "space" elements. The ratio of the frequency shift to the modulation rate is often called the modulation index.

An NCFSK signal can be demodulated by either a limiter-discriminator demodulator or a dual-filter demodulator. The former is more commonly used in practice, and its performance in the presence of atmospheric noise can be readily analyzed. Although matched-filter demodulators, of which the dual-filter demodulator is a close approximation, have been studied theoretically, the performance of this type of demodulator in the presence of atmospheric noise can only be approximately analyzed.

In many theoretical studies the ratio of energy per bit (element) to noise power density is used as the expression of signal-to-noise ratio — a convenient concept to work with when we compare or describe optimally designed modulation systems in the presence of Gaussian noise. In our study, however, where the systems are limited to NCFSK, nonoptimally designed systems should be considered, and the performance of systems in the presence of atmospheric noise should be analyzed. In this case, it is more convenient to start with the signal-to-noise ratio at the demodulator input, instead of the ratio of energy per bit to noise power density.

When several teletypewriter signals are to be transmitted simultaneously, either a time-division-multiplexing (TDM) or a frequency-division-multiplexing (FDM) technique is used. In a TDM-NCFSK system, a number of teletypewriter signals are time-division-multiplexed first, and the multiplexed signal is used to frequency-shift-key the RF carrier. The modulation rate in this system equals the number of teletypewriter signals times the modulation rate of a single-channel system. The type of emission is the same as that of a single-channel system, the modulated RF wave has a constant amplitude, and its performance can be analyzed in exactly the same manner as that of a single-channel system.

In an FDM-NCFSK system, on the other hand, a number of subcarriers or tones uniformly spaced in frequency, usually in a 3-kHz baseband, is used. Each subcarrier is frequency-shift-keyed by one teletypewriter signal, and the composite baseband signal of all the tones is transmitted as a sideband signal of an SSB-AM or an ISB-AM system. The modulation rate in each subchannel of an FDM-NCFSK system is the same as that of a single-channel system. The type of emission for this system is different from that of a single-channel or a TDM system, and the amplitude of the modulated RF wave is not constant. The performance of a single subchannel in an FDM-NCFSK system is analyzed in the same way as a single-channel NCFSK system. To obtain the required signal-to-noise ratio for an FDM-NCFSK system we have to multiply the required ratio for a single-channel system not only by the number of subchannels, but also by a factor corresponding to the ratio of the peak envelope power to the average power of the RF signal.

Radio waves propagated via the ionosphere suffer a number of unique perturbations, such as multipath, fast fading, frequency fluctuations, or phase fluctuations. Because of multipath distortion, the maximum modulation rate in a digital system is generally limited to the order of 100 to 200 bauds, and for this reason multiplexing in a TDM-NCFSK system is limited to, at most, four channels. Multipath distortion is the most important reason that FDM systems were developed for multichannel teletypewriter transmission over HF ionospheric channels.

Frequency fluctuations caused by propagation determine the minimum frequency spacing between two adjacent subcarriers and, therefore, the number of subcarriers that can be used in a given bandwidth. For this reason, the minimum modulation rate is limited by these frequency fluctuations if the total data signalling rate is to be kept constant.

Under adverse propagation conditions, an irreducible error probability exists beyond which increasing the signal-to-noise ratio has no effect. This problem has been analyzed in detail by Bello and Nelin (1962, 1963, 1964) and comprehensively surveyed by Akima (1967). We exclude it here and assume that no element errors are caused by distortion of the signal due to ionospheric propagation.

3.2 Teletypewriter Systems

Basically there are two teletypewriter systems: start-stop and synchronous systems. The two systems are significantly different in (1) the relation between teletypewriter speed and modulation rate, and (2) the relation between character error probability and binary element error probability.

The speed of a teletypewriter system is usually expressed in terms of words per minute. From the standpoint of modulation techniques, however, modulation rate is a factor of primary importance as the measure of transmission speed. The relation between teletypewriter speed expressed in words per minute (w/m) and modulation rate expressed in bauds can be obtained from the following observations:

(1) An average word is generally assumed to consist of six characters including one character corresponding to the space between words.

(2) In a start-stop system, one character consists of approximately 7.5 unit intervals, i.e., five information elements of unit interval plus a start element of unit interval and a stop element of approximately one and a half unit intervals.

(3) In a synchronous system, one character consists of six unit intervals, i.e., five information elements and a synchronizing element, all of unit interval.

Table 3 shows the modulation rates corresponding to some typical teletypewriter speeds; it does not cover all possible combinations of multiplexing techniques and teletypewriter systems, only those used in common practice.

The quality of teletypewriter transmissions is usually specified in terms of <u>character</u> error probability, while the basic quantity that is theoretically calculated is <u>element</u> error probability. When binary element errors occur independently of each other, the character error probability P_c is given as a function of the element error probability P_e by

$$P_c = 1-(1-P_e)^{17} \approx 17\, P_e$$

for a start-stop system, and by

$$P_c = 1-(1-P_e)^{5} \approx 5\, P_e$$

for a synchronous system (Watt et al., 1958). Table 4 shows the values of element error probability corresponding to some typical values of specified character error probability. When element errors are dependent, as is generally true for ionospheric HF channels, the element error probabilities can be greater for the given character error probabilities.

Table 3. Relation Between Teletypewriter Speed and Modulation Rate in 5-Unit Teletypewriter Systems

Channel Multiplexing	Teletypewriter System	Teletypewriter Speed (w/ m/ ch)	Modulation Rate (bauds)
Single-channel	Start-Stop	60	45
		100	75
	Synchronous	60	36
		100	60
Frequency-division-multiplexing	Start-Stop	60	45
		100	75
Two-channel time-division-multiplexing	Synchronous	60	72
		100	120
Four-channel time-division-multiplexing	Synchronous	60	144
		100	240

Table 4. Values of Element Error Probability P_e Corresponding to Some Typical Values of Character Error Probability P_c in 5-Unit Teletypewriter Systems

Teletypewriter System	P_c (%)	P_e (%)
Start-Stop	1	0.059
	0.1	0.0059
	0.01	0.00059
Synchronous	1	0.2
	0.1	0.02
	0.01	0.002

Since we use the values of element error probabilities in table 4, we obtain slightly pessimistic values of required signal-to-noise ratios for teletypewriter systems.

3.3 Basic Performance of a Single-Channel NCFSK System Under Stable Conditions

We shall first discuss the relation between signal-to-noise ratio and element error probability in a single-channel NCFSK system with a limiter-discriminator demodulator. When the modulation index is equal to or greater than one, but not so large that a low-pass filter between the discriminator and the decision-making circuit would have a significant effect on the performance, the element error probability P_e is equal to one-half the probability that the instantaneous noise amplitude will exceed the instantaneous signal amplitude (Montgomery, 1954a). Under stable conditions, therefore, the element error probability is one-half the amplitude probability distribution (APD) of the noise corresponding to the level of the signal; the APD of noise gives the percentage of time for which a specified level is exceeded by the noise envelope (CCIR, 1964).

In HF channels, the noise is mostly atmospheric. The APD of atmospheric noise can be represented sufficiently accurately for most applications by an appropriate curve chosen out of a family of idealized curves. In practice, the ratio of rms to average of the envelope voltage, denoted by V_d (in dB), is used to specify the curve that can be used to represent the distribution (Crichlow et al., 1960; Spaulding et al., 1962; CCIR, 1964). The family of idealized APD curves, with the values of V_d as a parameter, is given in CCIR (1964, fig. 27). For atmospheric noise, the value of V_d is greater than 1.049 dB, a value that applies to Gaussian noise.

Figure 8 shows the relation between the signal-to-noise ratio and the element error probability in a single-channel NCFSK system with a limiter-discriminator demodulator under stable conditions. To apply this figure, values of both the signal-to-noise ratio and the noise parameter V_d, measured at the input to the limiter, should be used. The relationship of the element error probability P_e being equal to one-half the probability that the instantaneous noise amplitude exceeds the instantaneous signal amplitude (Montgomery, 1954a) that is valid for an NCFSK system with a limiter-discriminator demodulator applies as well to an NCFSK system with a dual-filter demodulator (White, 1966), if the average power and the APD of the composite noise (the sum of the two noise outputs from the two bandpass filters) are known. When the passbands of the two bandpass filters are not widely separated in frequency, but not overlapping, the APD of the composite noise can be closely approximated by the noise that would be present in a bandwidth equivalent to the

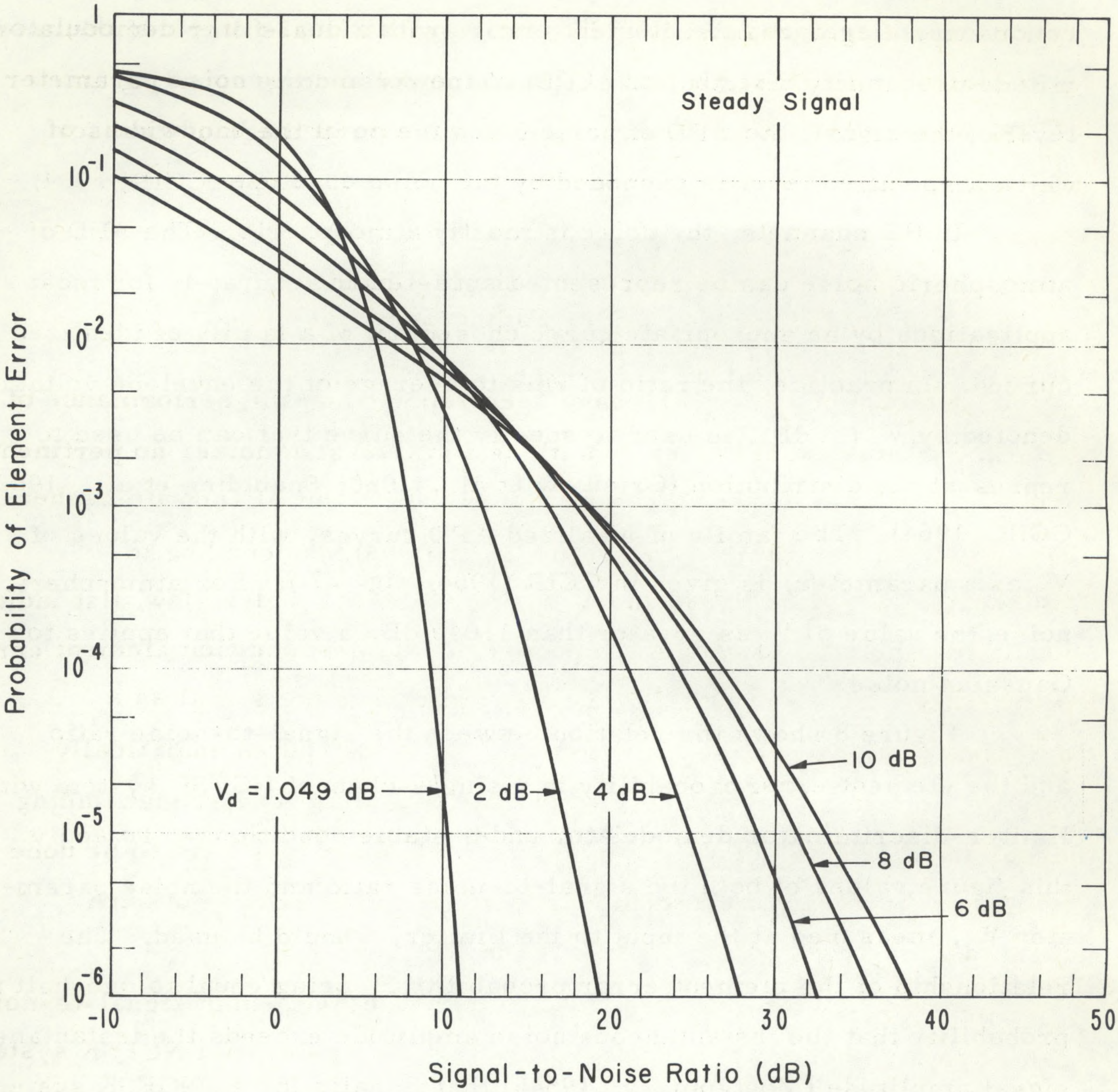

Figure 8. Element error probabilities in a single-channel NCFSK system under stable conditions. (Signal-to-noise ratio is the ratio of signal power to average noise power, and V_d is the ratio of rms to average of the noise envelope voltage, both measured at the input to the limiter in a limiter-discriminator demodulator, and measured in a bandwidth equivalent to the sum of the bandwidths of the two filters in a dual-filter demodulator. Modulation index is assumed to be not less than unity, and no low-pass filter is used before the decision-making circuit.)

sum of the bandwidths of the two filters. Therefore, figure 8 also applies to a single-channel NCFSK system with a dual-filter demodulator under stable conditions, if both the noise power and the noise parameter V_d are measured in a bandwidth equal to the sum of the bandwidths of the two filters.

3.4 Basic Performance of a Single-Channel NCFSK System Under Fading Conditions

Although many studies have been reported on the performance of NCFSK systems under fading conditions and Gaussian noise, no pertinent data are available in the literature that deal with the APD of atmospheric noise along the lines described by CCIR (1964). According to Montgomery (1954a), the element error probability under slow, flat fading conditions should be a weighted mean of the stable-condition element error probability with the probability density function of the signal as a weighting function. The weighted mean can be computed analytically only for certain signal and noise distributions, such as Rayleigh-fading signal and Gaussian noise; in most cases, computations have to be done by numerical integration techniques. Some typical results of such computations are shown in figures 9 and 10.

These figures show the relation between the median signal-to-noise ratio and the element error probability in a single-channel NCFSK system under Rayleigh-fading and log-normal-fading conditions, respectively, with no diversity and dual diversity of the selection-switching type. In figure 10, the fading range, defined as the difference in dB between the signal levels exceeded for 10 percent and 90 percent of the time, is assumed to be 13.4 dB, based on the fact that actually observed fading ranges over long-distance HF paths are of the same order as the value of 13.4 dB expected for the Rayleigh distribution (CCIR, 1967e).

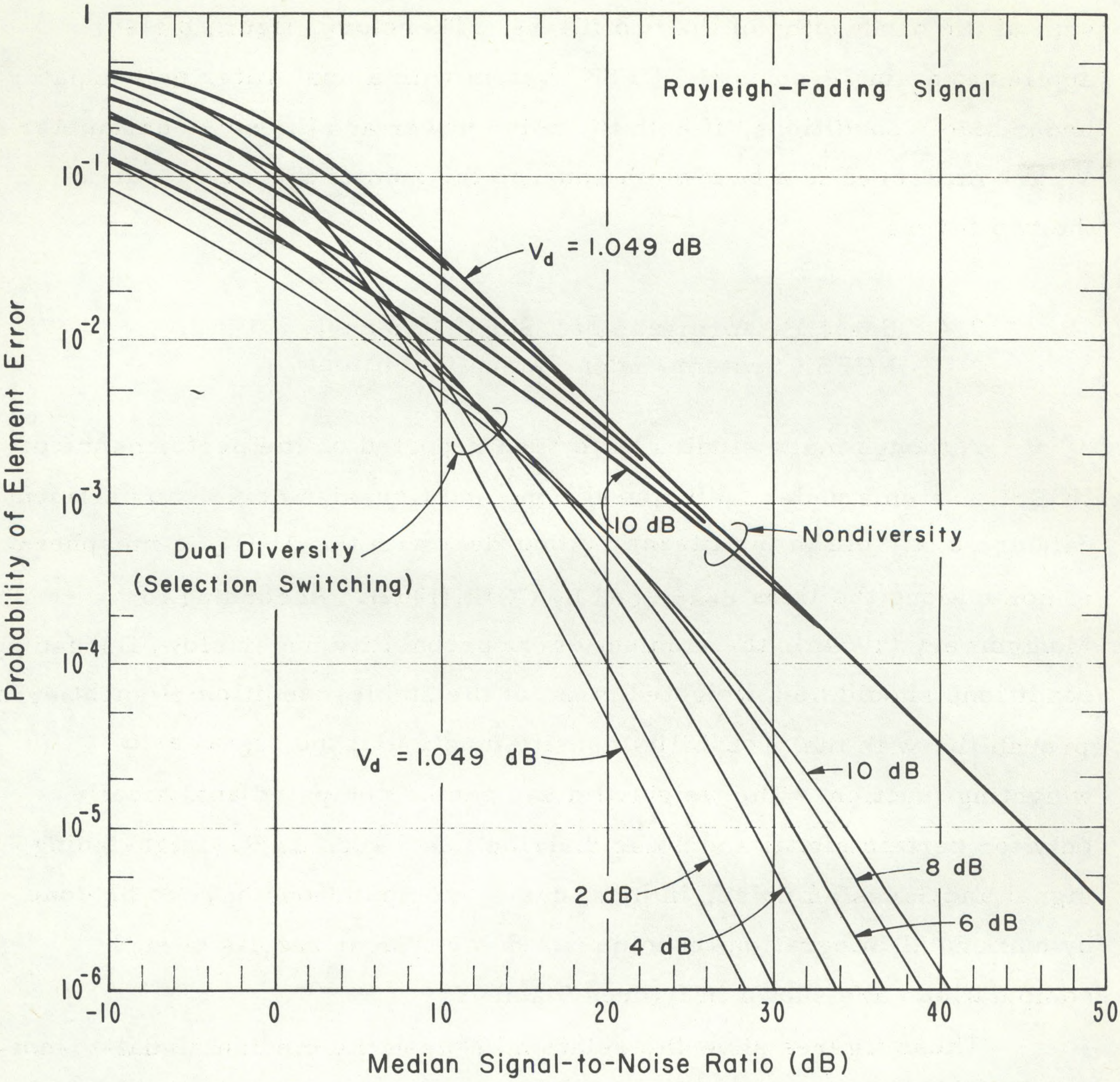

Figure 9. Element error probabilities in a single-channel NCFSK system under Rayleigh-fading conditions with no diversity and dual selection-switching diversity. (Median signal-to-noise ratio is the ratio of median signal power to average noise power, and V_d is the ratio of rms to average of the noise envelope voltage, both measured at the input to the limiter in a limiter-discriminator demodulator and measured in a bandwidth equivalent to the sum of the bandwidths of the two filters in a dual-filter demodulator. Modulation index is assumed to be not less than unity, and no low-pass filter is used before the decision-making circuit.)

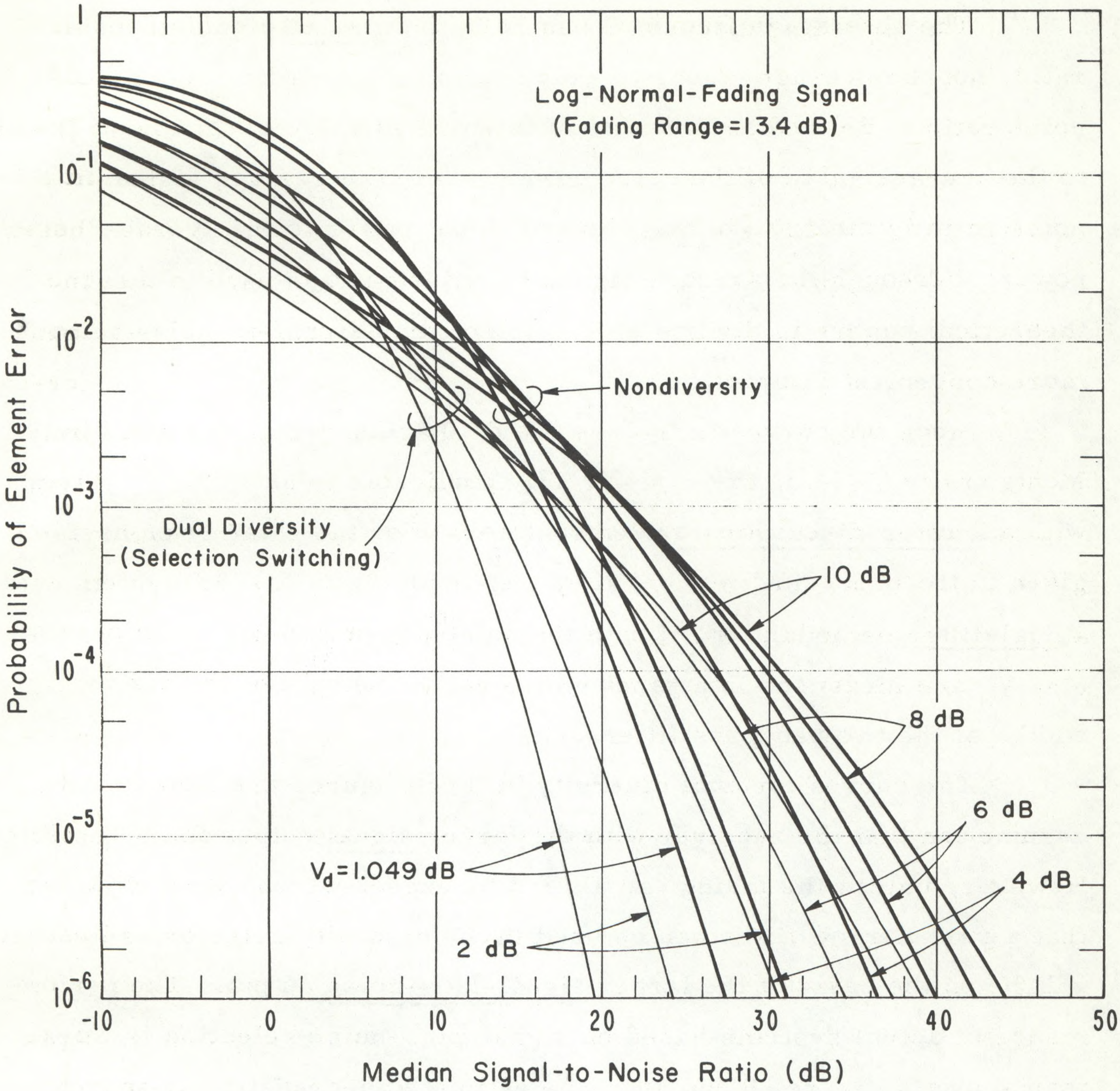

Figure 10. Element error probabilities in a single-channel NCFSK system under log-normal-fading conditions with no diversity and dual selection-switching diversity. (The fading range is assumed to be 13.4 dB, which is the same as that expected for Rayleigh-fading. Median signal-to-noise ratio is the ratio of median signal power to average noise power, and V_d is the ratio of rms to average of the noise envelope voltage, both measured at the input to the limiter in a limiter-discriminator demodulator, and measured in a bandwidth equivalent to the sum of the bandwidths of the two filters in a dual-filter demodulator. Modulation index is assumed to be not less than unity, and no low-pass filter is used before the decision-making circuit.)

The abscissa in figures 9 and 10 is the median signal-to-noise ratio, not the average signal-to-noise ratio. The median signal-to-noise ratio is defined as the ratio of the median value of the signal power to the average value of the noise power, while the average signal-to-noise ratio is the ratio of the average signal power to the average noise power. Although the average signal-to-noise ratio is used in most theoretical papers in the literature, the median signal-to-noise ratio is more convenient in practice.

Since the curves in figures 9 and 10 are based on the work by Montgomery (1954a), they are directly applicable to an NCFSK system with a limiter-discriminator demodulator. For the same reasons as given in the preceding section, they also apply to an NCFSK system with a dual-filter demodulator, if both the noise power and the noise parameter V_d are measured in a bandwidth equal to the sum of the bandwidths of the two bandpass filters.

The curves for dual diversity in these figures are based on the assumption that the receiver with the larger signal output can be selected. However, unless the fading can always be expected to be very slow, so that a very narrow filter can be used in the diversity selector, selection will be on the basis of the larger signal-plus-noise output. The performance of actual systems based on signal-plus-noise selection is worse than shown in figures 9 and 10. The estimated degradation is approximately 1 dB for element error probabilities of practical interest (Montgomery, 1954b). The curves for dual diversity in these figures are applicable to NCFSK systems with dual selection-switching diversity, no matter where the switching takes place, as long as the selection is based on the comparison of the signals at the RF or IF stages of the receivers.

Selection-switching combining is not the only diversity combining technique. Others are maximal-ratio combining (Kahn, 1954; Brennan, 1955) and equal-gain combining (Altman and Sichak, 1956). There are also a number of variants of diversity systems, corresponding to possible combinations of combining techniques, demodulator types, and location of combining. Performance is independent of demodulator type, if the combining is made before the demodulator (in the RF or IF stages of the receivers), but is dependent on the actual demodulators used if combining is effected after demodulation.

Maximal-ratio combining diversity is optimum if the combining can be done before the demodulator. Equal-gain and selection-switching combining are 0.6 dB and 1.5 dB, respectively, worse than optimum maximal-ratio combining for Rayleigh-fading signal and Gaussian noise (Altman and Sichak, 1956). A series of studies might suggest that the performance of predetection equal-gain combining is actually better than postdetection maximal-ratio combining (Adams and Mindes, 1958; Brennan, 1959; Locke, 1960).

The curves for dual diversity in figures 9 and 10 are based on the assumption of complete statistical independence of the fading at the two diversity antennas, which can rarely be achieved. For dual diversity, however, correlation of the fading does not result in a large loss if the correlation coefficient is moderate. For example, losses due to correlation coefficients of 0.4 and 0.6 are approximately 1 dB and 2 dB, respectively, for dual diversity maximal-ratio predemodulation combining in the presence of Rayleigh-fading and Gaussian noise (Pierce, 1958).

3.5 Required Signal-to-Noise Ratios for Single-Channel NCFSK Systems

As shown in figures 8 through 10, the required signal-to-noise ratio for a specific element error probability depends largely on the noise parameter V_d, except for Rayleigh-fading without diversity at error probabilities of less than 10^{-3}. The parameter V_d in turn depends largely on the season, the local time of day, the operating frequency, and the receiver bandwidth (CCIR, 1964). Signal-to-noise ratio is of primary importance in determining the lowest useful frequency (LUF), i.e., in the lower region of the HF band, where the value of V_d is almost independent of the season and the local time. It is estimated to be around 6 dB for a receiver bandwidth of 200 Hz.

With element error probabilities corresponding to character error probabilities of 1 percent, 0.1 percent, and 0.01 percent given in table 4, the values of the required signal-to-noise ratios for a single-channel NCFSK system for corresponding character error probabilities can be read from figures 8 through 10. Table 5 shows the required signal-to-noise ratios thus obtained for V_d = 6 dB. We suggest that the values in this table be used for single-channel NCFSK systems over HF ionospheric paths in the lower region of the HF band.

The value of V_d, and thus the required signal-to-noise ratio, is dependent on the bandwidth. However, a relatively small difference in the bandwidth results in only a small difference in the required signal-to-noise ratio. For example, changing the bandwidth from 200 Hz to 170 Hz results in a change in the value of V_d from 6 dB to 5.5 dB, based on the conversion diagram for V_d given in CCIR (1964). We can see from figures 8 through 10 that the difference in required signal-to-noise ratio caused by this difference does not exceed 1 dB.

When the IF bandwidth is much wider than 200 Hz, the noise parameter V_d is greater than 6 dB, and, if no low-pass filter is used between the discriminator and the decision-making circuit, the required signal-to-noise ratios are also greater than those given in table 5. When a low-pass filter is used, as it generally is in a wideband system, the required signal-to-noise ratios are expected to be improved to such an extent that the degradation produced by the greater V_d will be compensated for, although no analysis has been made of the effectiveness of using a low-pass filter. Therefore, the use of table 5 is suggested for wideband systems as well.

Table 5. Required Signal-to-Noise Ratios for a Single-Channel NCFSK System Over HF Ionospheric Paths in the Lower Region of the HF Band

Teletypewriter System	Character Error Probability P_c (%)	Required Signal-to-Noise Ratio (dB)				
		Stable condition	Rayleigh fading		Log-normal-fading (fading range 13.4 dB)	
			No diversity	Dual diversity	No diversity	Dual diversity
Start-Stop	1	19.6	27.5	19.8	23.2	19.1
	0.1	25.4	37.7	26.7	30.2	25.8
	0.01	29.9	47.7	32.6	36.1	31.0
Synchronous	1	15.7	21.7	15.3	18.7	14.8
	0.1	22.5	32.3	23.2	26.8	22.5
	0.01	27.6	42.3	29.5	33.2	28.4

Signal-to-noise ratio is the ratio of signal power to average noise power and is the ratio of median signal power to average noise power for fading signals. Average noise power is measured at the input to the limiter in a limiter-discriminator demodulator, in a bandwidth equivalent to the sum of the bandwidths of the two filters in a dual-filter demodulator. The noise parameter V_d, measured in the same bandwidth as in the measurement of noise power, is assumed to be 6 dB. Modulation index is assumed to be not less than unity.

The uncertainty associated with the V_d value of 6 dB on which table 5 is based is estimated to be on the order of 1.5 dB, and the uncertainty in the required signal-to-noise ratio resulting from the uncertainty in estimating V_d is estimated not to exceed 2 dB, both in terms of standard deviation.

The curves in figures 8 through 10, and therefore the values in table 5, are based on the idealized APD of atmospheric noise. But the shape of the APD of atmospheric noise is not necessarily the same as the idealized APD. The uncertainty in the level exceeded by the noise envelope for a specified percentage of time of interest here, introduced by possible variations in the shape of the APD, is estimated to be approximately 2 dB in terms of standard deviation for V_d = 6 dB. The uncertainty in the required signal-to-noise ratios resulting from the variations in the shape of the APD is estimated to be the same, i.e., 2 dB in terms of standard deviation.

The values of required signal-to-noise ratios for dual diversity are based on the analysis for selection-switching combining. As described in the preceding section, possible gain obtainable by using different diversity techniques is relatively small. Loss of diversity improvement because of correlated fading is anticipated, but this is also small. Therefore, we suggest the use of the values in table 5 for any type of diversity technique. Uncertainty from this simplification of diversity techniques is estimated to be 1 dB in terms of standard deviation.

We are concerned with the hourly median values of the signal-to-noise ratios. Because the log-normal-fading model is better suited than the Rayleigh-fading model to hourly statistics (CCIR, 1967e), we propose to adopt as the required signal-to-noise ratios for fading signals the values corresponding to log-normal fading in the last two columns in table 5. We can see that the differences in required signal-to-noise ratios in the different fading models are very small for V_d = 6 dB when dual diversity techniques are used.

The values for log-normal fading in table 5 are based on a fading range of 13.4 dB. Dispersion of several dB around this value has been observed (CCIR, 1967e) and the uncertainty in required signal-to-noise radio for log-normal fading resulting from this dispersion of the fading range is estimated to be approximately 2 dB from our computation results.

In summary, we suggest the use of the values given in the third column in table 5 as the required signal-to-noise ratios under stable conditions, and the use of the values given in the last two columns as the required signal-to-noise ratios under fading conditions. The standard deviation associated with these suggested values of required signal-to-noise ratios are estimated to be 3 dB and 4 dB for stable conditions and fading conditions, respectively.

3.6 Required Signal-to-Noise-Density Ratios for Some Typical NCFSK Systems

In this section, we derive the required signal-to-noise-density ratios for some typical NCFSK systems from the required signal-to-noise ratios determined in the preceding section.

The procedure for deriving the required signal-to-noise-density ratios, expressed in dB, is quite simple and straightforward for either a single-channel or a time-division-multiplexed (TDM) NCFSK system. All we have to do is to add $B = 10 \log_{10} b$ to the required signal-to-noise ratio expressed in dB, where b is the receiver bandwidth in Hz. The required signal-to-noise-density ratios for some typical single-channel and TDM-NCFSK systems over HF ionospheric paths in the lower region of the HF band thus obtained are given in table 6.

To derive the required signal-to-noise-density ratios for a frequency-division-multiplexed (FDM) NCFSK system from the required signal-to-noise ratios is somewhat more complicated. The procedure consists of: (1) adding $B = 10 \log_{10} b$, where b is the bandwidth of a

Table 6. Required Signal-to-Noise-Density Ratios for Some Typical Single-Channel and TDM-NCFSK Systems Over HF Ionospheric Paths in the Lower Region of the HF Band

Type of Service		Character Error Probability	Required Signal-to-Noise-Density Ratio (dB)		
				Fading condition	
Emission designation	Description	P_c (%)	Stable condition	No diversity	Dual diversity
1.1 F1	Single-channel NCFSK 60 w/m; start-stop teletype 1500-Hz bandpass filter	1	51	55	51
		0.1	57	62	58
		0.01	62	68	63
1.7 F1	4-channel TDM-NCFSK 60 w/m/ch; synchronous teletype 1500-Hz bandpass filter	1	47	50	47
		0.1	54	59	54
		0.01	59	65	60
2.85 F1	4-channel TDM-NCFSK 100 w/m/ch; synchronous teletype 2850-Hz bandpass filter	1	50	53	49
		0.1	57	61	57
		0.01	62	68	63

Signal-to-noise-density ratio is the ratio of signal power to average noise power contained in a 1-Hz bandwidth, where signal power should be interpreted as median signal power for fading conditions.

teletypewriter channel; (2) adding $N = 10 \log_{10} n$, where n is the number of teletypewriter channels; and (3) adding an appropriate crest factor (or loading factor), which is related to the ratio of the peak-envelope power to the average power of the multiplexed signal. Addition of the crest factor is necessary since we want to express the required signal-to-noise ratio in terms of the ratio of signal peak envelope power (not average power) to noise power.

When n tones of equal amplitude are frequency-division-multiplexed, the average power of the resultant FDM signal is n times that of one tone, while the peak envelope power is n^2 times that of one tone. Since the peak envelope power is equal to the average power in a tone, the crest factor is equal to $10 \log (n^2/n) = 10 \log n$ dB in an FDM signal. When n is relatively small, say 5 or less, this relation should be used.

For greater n, however, the crest factor will be lower than 10 log n dB. As n increases, the APD of the FDM signal approaches that of Gaussian noise, and the probability that the signal envelope exceeds a certain level, lower than its theoretical maximum, becomes very small. For example, the levels of rms plus 6.1 dB and 6.5 dB are exceeded 1 percent of the time by the envelope of FDM signals of n = 6 and n = 9, respectively (Slack, 1946), while the level exceeded by the envelope of Gaussian noise for the same time period is the rms plus 6.6 dB. The FDM signal can be peak-clipped at such a level without causing serious distortion of the waveform or element errors. Styers (1961) analyzed the effects of multiple tone clipping and showed that, for a 20-tone signal, no appreciable increase in the binary error probability will be noted for peak clipping of 6 dB (at the level of 6 dB below the theoretical maximum). This indicates that the crest factor can be as low as 7 (=10 log 20 - 6) dB for n = 20. Although Styers' analysis was made for a phase-shift-keyed (PSK) system, the results are applicable to FSK systems as well.

Based on these observations, we shall use the value of 7 dB in the rest of this report as an estimate of the crest factor of FDM signals for n = 6 or greater.

The required signal-to-noise-density ratios for some typical FDM–NCFSK systems over HF ionospheric paths in the lower region of the HF band thus obtained are given in table 7. Standard deviations associated with the values in both tables 6 and 7 are estimated to be 3 dB and 4 dB for stable conditions and fading conditions, respectively.

3.7 Summary for Digital Communication Systems

The results of our study for digital communication systems are as follows:

(1) The relation between teletypewriter speed and modulation rate is given in table 3 (sec. 3.2).

(2) The relation between element error probability and character error probability is given in table 4 (sec. 3.2).

(3) Based on Montgomery's (1954a) analysis and the atmospheric-noise waveform data (CCIR, 1964), the relation between signal-to-noise ratio and element error probability is calculated for a steady (nonfading) signal and is shown in figure 8 (sec. 3.3).

(4) Based on the same analysis and data as above, the same relations are calculated for a Rayleigh-fading signal and a log-normal-fading signal, with or without dual diversity, and are shown in figures 9 and 10, respectively (sec. 3.4).

(5) A value of 6 dB is estimated as typical of the noise parameter V_d applicable to the lower portion of the HF band. Based on this value, the required signal-to-noise ratios for a single-channel NCFSK system are estimated and are given in table 5 (sec. 3.5).

Table 7. Required Signal-to-Noise-Density Ratios for Some Typical FDM-NCFSK Systems Over HF Ionospheric Paths in the Lower Region of the HF Band

Type of Service		Character Error Probability P_c (%)	Required Signal-to-Noise-Density Ratio (dB)		
				Fading condition	
Emission designation	Description		Stable condition	No diversity	Dual diversity
3A7J	16-channel FDM-NCFSK, 100 w/m/ch; start-stop teletype; limiter-discriminator demodulator; 110-Hz bandpass filter in each channel.	1	59	63	59
		0.1	65	70	65
		0.01	69	76	70
3A7J	16-channel FDM-NCFSK 100 w/m/ch; synchronous teletype; limiter-discriminator demodulator; 110-Hz bandpass filter in each channel.	1	55	58	54
		0.1	62	66	62
		0.01	67	73	68
3A7J	12-channel FDM-NCFSK 60 w/m/ch; start-stop teletype; dual-filter demodulator; two 85-Hz bandpass filters in each channel.	1	60	63	59
		0.1	66	70	66
		0.01	70	76	71
3A7J	6-channel FDM-NCFSK; dual inband diversity; 60 w/m/ch; start-stop teletype; dual-filter demodulator; two 85-Hz bandpass filters in each channel.	1	---	---	59
		0.1	---	---	66
		0.01	---	---	71

Signal-to-noise-density ratio is the ratio of peak envelope power of the signal to average noise power contained in a 1-Hz bandwidth where the peak envelope power of the signal should be interpreted as its median value for fading conditions.

(6) The use of the values for stable conditions in the third column in table 5 is recommended, with an estimated standard deviation of 3 dB.

(7) For fading conditions, the use of the values for log-normal fading in the last two columns in table 5 is recommended, with an estimated standard deviation of 4 dB.

(8) The required signal-to-noise-density ratios for some typical NCFSK systems are given in tables 6 and 7 (sec. 3.6). Standard deviations of 3 dB and 4 dB apply to these values for stable and fading conditions, respectively.

4. OTHER COMMUNICATION SYSTEMS

4.1 Composite Voice and Teletypewriter Systems

As typical composite systems, we consider independent-sideband amplitude-modulation (ISB-AM) systems, transmitting 16 teletypewriter signals plus one, two, or three voice signals. We assume that the teletypewriter signals are multiplexed to form a 16-channel FDM-NCFSK signal identical to either the one listed at the top or the one listed second from the top in table 7 (sec. 3.6).

In these systems, the teletypewriter channels are generally the essential services, and the quality is assessed or specified in terms of character error probability in teletypewriter messages. We assume that the transmitter is loaded in such a way that the values of the peak envelope power of the multiplexed teletypewriter signals are 80 percent, 60 percent, and 50 percent of the rated peak envelope power of the transmitter, and the values of the voice signals are 20 percent, 40 percent, and 50 percent of the rated peak envelope power of the transmitter, when one, two, and three voice signals, respectively, are transmitted together with the teletypewriter signals. There is a probability that the values of the peak envelope power of the composite signals may exceed the rated values of the peak envelope power of the transmitters, but we assume that this probability is very small and that the effect of peak limiters on the error probabilities, which prevent overloading of the transmitters, is negligible. Then, the required signal-to-noise-density ratios for the composite systems can be obtained by adding 1.0 dB, 2.2 dB, and 3.0 dB to those for the 16-channel FDM-NCFSK systems listed first and second in table 7. The results are given in table 8. Note that, under the assumption of such transmitter loading, the required signal-to-noise-density ratio for just usable quality voice transmission is always exceeded if a character error probability of 1 percent or less is achieved in teletypewriter transmission.

Table 8. Required Signal-to-Noise-Density Ratios for Some Typical Composite Voice and Teletypewriter Systems Over HF Ionospheric Paths in the Lower Region of the HF Band

Type of Service		Character Error Probability in Teletype Message P_c (%)	Required Signal-to-Noise Density Ratio (dB)		
Emission designation	Description		Stable condition	Fading condition: No diversity	Fading condition: Dual diversity
6A9B	16-channel FDM-NCFSK (as listed at the top of table 7) and one voice signal.	1	60	64	60
		0.1	66	71	66
		0.01	70	77	71
9A9B	16-channel FDM-NCFSK (as listed at the top of table 7) and two voice signals.	1	61	65	61
		0.1	67	72	67
		0.01	71	78	72
12A9B	16-channel FDM-NCFSK (as listed at the top of table 7) and three voice signals.	1	62	66	62
		0.1	68	73	68
		0.01	72	79	73

Table 8. (continued)

6A9B	16-channel FDM-NCFSK (as listed at the second from the top of table 7) and one voice signal.	1	56	59	55
		0.1	63	67	63
		0.01	68	74	69
9A9B	16-channel FDM-NCFSK (as listed at the second from the top of table 7) and two voice signals.	1	57	60	56
		0.1	64	68	64
		0.01	69	75	70
12A9B	16-channel FDM-NCFSK (as listed at the second from the top of table 7) and three voice signals.	1	58	61	57
		0.1	65	69	65
		0.01	70	76	71

Transmitter loadings of 80 %, 60 %, and 50 % of the rated peak envelope power of the transmitter by teletypewriter signals are assumed for 6A9B, 9A9B, and 12A9B emissions, respectively. Signal-to-noise-density ratio is the ratio of peak envelope power of the signal to average noise power contained in a 1-Hz bandwidth where the peak envelope power of the signal should be interpreted as its median value for fading conditions.

The same standard deviations as in the NCFSK systems apply to these composite systems, i.e., 3 dB and 4 dB for stable conditions and fading conditions, respectively.

4.2 Aural-Reception Radiotelegraphy

Our study has not revealed any evidence suggesting the necessity of revising the values of required signal-to-noise ratios given by ARPA (Silva, 1964) for radiotelegraphy with on-off keying (A1 emission) and aural reception. Based on several test results, ARPA gives values of -2 dB and 6 dB as the required ratios of signal power to noise power in a 6-kHz bandwidth for stable conditions and fading conditions, respectively. These values correspond to values of 36 dB and 44 dB in terms of required signal-to-noise-density ratios.

4.3 Phototelegraphy (Facsimile)

No evidence has been found that might suggest the necessity of revising the values of required signal-to-noise ratios for A4 phototelegraphy (facsimile) given by CCIR (1967b, c) and adopted by ARPA (Silva, 1964), which gives values of 12 dB and 21 dB as the required ratios of signal power to noise power in a 6-kHz bandwidth for stable conditions and fading conditions, respectively. These values correspond to values of 50 dB and 59 dB in terms of required signal-to-noise-density ratios.

5. SUMMARY AND CONCLUSIONS

Required signal-to-noise ratios for various HF communication systems have been estimated. The study was begun with emphasis on an extensive literature search, rather than original work in analyzing system performances.

A main difficulty encountered in the study of voice communication systems was created by the wide disparity among published data. The results given in this report represent an averaging of these data, with an indication given of the estimated standard deviation.

Another difficulty was encountered in the study of digital communication systems. Despite the tremendous number of published analyses of the performance of various digital communication systems, very little useful information applicable to the present study could be found. Surprisingly, certain aspects of the performance of an NCFSK system in the presence of atmospheric noise had to be evaluated in the course of the study.

For convenience of application, the results are given in terms of signal-to-noise-density ratios rather than signal-to-noise ratios. They are as follows:

(1) Required signal-to-noise-density ratios for voice communication of just usable quality are estimated by averaging the data from various sources. They are given in table 2, section 2.9. The standard deviation associated with those values is estimated to be 5 dB.

(2) Retention of the values of required signal-to-noise ratios, given by CCIR (1967 b, c) and adopted by ARPA (Silva, 1964), is recommended for voice communication of good commercial quality. The values, converted to required signal-to-noise-density ratios, are given in table 2, section 2.9.

(3) Required signal-to-noise-density ratios for NCFSK systems transmitting teletypewriter signals are estimated on the basis of the CCIR noise data (CCIR, 1964) and of the log-normal-fading model for fading conditions (CCIR, 1967e). The results are given in table 6 for single-channel and TDM-NCFSK systems and in table 7 for FDM-NCFSK systems, section 3.6. The standard deviations associated with those values are estimated to be 3 dB and 4 dB for stable conditions and fading conditions, respectively.

(4) Estimated required signal-to-noise-density ratios for composite voice and teletypewriter systems are given in table 8, section 4.1. The estimated standard deviations associated with these values are 3 dB and 4 dB for stable and fading conditions, respectively.

(5) Retention of the values of required signal-to-noise ratios, given by ARPA (Silva, 1964), is recommended for A1-emission, aural-reception radiotelegraphy. Required signal-to-noise-density ratios are 36 dB and 44 dB under stable and fading conditions, respectively.

(6) Retention of the values of required signal-to-noise ratios, given by CCIR (1967b, c) and adopted by ARPA (Silva, 1964), is recommended for A4 phototelegraphy (facsimile). Required signal-to-noise-density ratios are 50 dB and 59 dB under stable conditions and fading conditions, respectively.

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