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Speeding-Up of HF Radiotransmissions and Broadcasts (World Weather Watch Study T.21)

HIROSHI AKIMA

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FOREWORD

The studies described in this report were performed by the Institute for Telecommunication Sciences and Aeronomy for and with the support of the Office of World Weather Systems, Environmental Science Services Administration, Washington, D. C. The work was performed under Environmental Science Services Administration Project 291102000.

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SPEEDING-UP OF HF RADIOTRANSMISSIONS AND BROADCASTS (WORLD WEATHER WATCH STUDY T. 21)

Hiroshi Akima

Technical problems arising from the use of HF radio circuits for the global telecommunication system in the World Weather Watch (WWW) plan are reviewed. Propagation factors affecting HF communications are delineated, modulation-demodulation techniques as well as error control procedures to be used for HF high-speed data transmission are reviewed and consolidated, and technical problems concerning HF meteorological broadcasts are discussed. Several technical recommendations for the design of the WWW global telecommunication system are made, based on these studies.

1. INTRODUCTION

1.1. Background

In response to a resolution unanimously adopted in the General Assembly of the United Nations in 1960, the World Meteorological Organization (WMO) is now planning a new world weather system to which the name World Weather Watch (WWW) has been given [WMO, 1966]. An improved global telecommunication system is now being designed, as an essential part of the new system.

Various member administrations of the WMO are undertaking specific tasks in the design of the telecommunication system. The United States was asked to participate in Study T. 21, "Speeding-up of HF radiotransmissions and broadcasts", as one of the tasks [Davies, 1966]. The purpose of this task is to develop a set of technical recommendations for high-speed data transmission over HF circuits and high-rate HF meteorological broadcasts. The United States effort in response to this request is being coordinated by the Environmental Science Services Administration (ESSA), under the Office of World Weather Systems. The Ionospheric Telecommunications Laboratory of the Institute for Telecommunication Sciences and Aeronomy (ITSA) has undertaken the study program.

1.2. An Outline of the WWW Global Telecommunication System

The task of the global telecommunication system is to collect weather observation data from all parts of the world, to transmit them rapidly to the National Meteorological Centers (NMC's), Regional Meteorological Centers (RMC's), and World Meteorological Centers (WMC's), and to provide a means by which the analysis and forecasts based on the data can be given the required distribution. Both speed and reliability are essential for this system.

A high-speed circuit called the "main trunk circuit" will connect the three WMC's and a number of RMC's, NMC's, and Regional Telecommunication Hubs (RTH's). (When the duties of RMC's are confined to the operation of telecommunication facilities, they will be termed RTH's.) Adequate telecommunications to bring material to and from the points connected to the main trunk circuit are also required. Neither the locations nor the precise functions of RMC's and RTH's have yet been finally decided. The WMC's, RMC's, and RTH's will be equipped with telecommunication computers, i.e., electronic computers which are programmed to perform the functions of automatic selection, switching, and editing.

The precise amount of data to be transmitted has not yet been decided. However, some suggested figures concerning daily traffic load on the main trunk circuit [Wüsthoff, 1966] are given in table 1.

Table 1. Suggested daily traffic load on the main trunk (It is assumed that the permitted daily transmission time is 19.2 hours, i.e., 80% of 24 hours.)

telecommunication code	8-bit code		4-bit code	
transmission rate (bits/sec)	1200	2400	1200	2400
transmission time to be used (hours)	15.3	7.7	7.7	3.9
time available for additional transmission (hours)	3.9	11.5	11.5	15.3

Guidelines for the design of the telecommunication system have been established by Final Reports on WWW Studies T.1 [Wüsthoff, 1966] and T.2 [Thompson, 1966]. (Recommendations made in these reports are listed in the Appendices.) Some important features of the system which are taken into account in the present study will be described.

As recommended in Final Report on Study T.1, the technical characteristics of the telecommunication circuits will be, as far as possible, in conformity with the approved Recommendations of the International Telegraph and Telephone Consultative Committee (CCITT), the International Radio Consultative Committee (CCIR), and the International Organization for Standardization (ISO).

Special-quality telephone-type circuits (bandwidth 3100 Hz) will be leased, wherever possible, in point-to-point systems. Where wire circuits are not available, radio circuits will be used. In addition to point-to-point circuits, HF radio broadcasts will play an important role in distributing observational data in some parts of the world during an interim period.

The data signalling rate will be 2400 bits/second in the high-speed point-to-point system, i.e., main trunk circuits and connections to the RMC's and RTH's. (The data signalling rate is given by

$$\sum_{i=1}^{i=m} \frac{1}{T_i} \log_2 n_i$$

and expressed in bits/second, where m is the number of parallel channels, T_i is the minimum interval for the ith channel in seconds, and n_i is the number of significant conditions of the modulation in the ith channel [CCITT, 1964].) Where this rate cannot be implemented at the beginning, the rate can be 1200 bits/second for an interim (first) phase, but it should be 2400 bits/second in the final (second) phase.

An error-control system will be used in the circuits of the WWW global telecommunication system connecting the WMC's, RMC's, and RTH's. The error-control system will be part of the data terminal equipment and not a part of the data communication channel. (The operation of the data communication channel shall not modify the data stream nor require interruption of the data stream at the point of interface to the information channel.) The error-control will be performed by a computer.

1.3. Scope and Objectives

The purpose of the present study [Davies, 1966] is to develop a set of technical recommendations based upon technical developments in the fields of

(1) medium and high-speed data transmission using HF point-to-point radio circuits, and

(2) meteorological broadcasting in particular using higher modulation rates (say, 75 bauds or even higher)

for the WWW global telecommunication system. (Medium-speed data transmission is defined as the data signalling rate between 200 and 1200 bits/second, and high-speed data transmission is defined as a data signalling rate above 1200 bits/second [Davies, 1966]. The modulation rate is defined as the reciprocal of the unit interval measured in seconds and is expressed in bauds [CCITT, 1964].)

The specific items covered are:

(1) to define and delineate HF propagation factors and channel characteristics affecting high-speed data transmission;

(2) to review the various types of modems (modulators and demodulators) in use for high-speed HF data transmissions, indicating the types of modulation and multiplexing employed, demodulation processes, etc., and to indicate the basis for choosing these techniques for HF rather than others in common use for non-HF circuits;

(3) to review and consolidate the various theoretical and experimental studies of HF data transmissions which have been performed, in order to present a composite picture of the problems and state of knowledge regarding such communications;

(4) from all of the above, to summarize the probable limitations to high-speed HF data transmissions;

(5) to describe error statistics and applicable error control techniques for HF circuits;

(6) to review the various techniques in use for HF meteorological broadcasts, and to describe the problems arising from speeding up of the broadcasts;

(7) to identify particular difficulties to be expected for specific paths in question (e.g., high interference levels in southeast Asia, equatorial fading, etc.); and

(8) to recommend general rules for the design and selection of equipments and techniques for high-speed HF data transmission circuits and high-rate HF meteorological broadcasts, and for the operation of such circuits.

2. PROPAGATION FACTORS AFFECTING HF COMMUNICATION

2.1. Long-Term Propagation Effects

There are diurnal, seasonal, and solar-cycle variations in the characteristics of the ionosphere. Factors of practical importance are:

(1) changes in ionization in the upper ionospheric regions, resulting in variations in the Maximum Usable Frequency (MUF) [CCIR Recommendation 373-1];

(2) changes in ionization in the lower ionospheric regions, resulting in increased attenuation of sky-wave signals due to absorption in these regions, causing variation in the Lowest Useful Frequency (LUF), circuit signal-to-noise ratio (SNR), and reliability;

(3) variations in the natural noise background due to variation in the geographic location and the frequency of lightning discharges, coupled with the variation in propagation of these noise bursts in accordance with (1) and (2) above; and

(4) the severity of interference from unwanted radio transmitters which is also associated with (1) and (2) above.

As will be described later, many of the long-term variations of the above factors are predictable and methods have been developed to estimate the performance of HF circuits by considering variations from hour to hour within a day, from month to month, and throughout the solar cycle. Day-to-day variations within a month are handled only on a statistical basis and no long-term predictions are currently available for specific days.

There are several peculiarities in HF propagation associated with the equatorial ionosphere. These problems are being studied under CCIR

Question 6/VI, and some of the results are described in CCIR Report 343. The ionosphere in the daytime F region is very thick, its peak appears at a real height of 400 to 500 km, and its electron density is great. One-hop propagation paths in excess of 10,000 km may appear in equatorial regions as a result of the great layer height. While the temperate latitude sporadic E layer is extremely irregular in time and space, another type of sporadic E layer appears almost regularly during daylight hours in the equatorial region, and propagation of HF waves is influenced by this layer.

There are some areas, e.g., southeast Asia, where high interference levels from other transmitters are observed. This is caused not only by the propagation conditions in that area, but also because some countries do not respect the regulations concerning the frequency allocation set by the International Telecommunication Union (ITU).

Separate predictions are usually necessary for each circuit under consideration, but it is possible to make the following general statements about the more important long-term variations.

a. Maximum Usable Frequency

On a given day the MUF reaches its minimum value just prior to sunrise and normally reaches maximum shortly after local noon at the path mid-point. Largest diurnal variations of MUF occur in the winter months with a maximum MUF near noon. The MUF generally increases with an increase in solar activity.

b. Lowest Useful Frequency

The LUF is normally maximum at local noon at the path mid-point and minimum during periods when darkness extends over the entire path within a day. The LUF's are dependent upon the angle of the sun, normally reaching a maximum when the sun is at maximum elevation above the horizon. The LUF's generally increase during daytime as solar activity increases but the nighttime LUF's are essentially the same throughout the solar cycle.

c. Circuit Reliability

Circuit reliability as estimated by available SNR for frequencies within the MUF/LUF range is normally maximum during the afternoon hours and minimum just before dawn within a day. Reliability is maximum during winter days and minimum in winter pre-dawn within a year. Although both the MUF and the LUF increase with solar activity, the increase in MUF is normally greater than the increase in LUF, and therefore, reliability for a given frequency complement is better during periods of high solar activity. However, higher frequencies are required during those periods.

d. Interference

During the morning hours at any receiving site, interference will be most likely at the higher frequencies from transmitters located to the east of the receiving site and on the lower frequencies from the west. In the afternoon and evening the converse is true. Since power and antenna patterns as well as propagation conditions affect interference, specific calculations are often required to estimate probable times of maximum interference. The interference problem becomes less severe as solar activity increases, because normally a wider range of frequencies becomes available for each communication circuit.

2.2. Short-Term Propagation Effects

HF signals reflected from the ionosphere usually arrive at the receiver by several paths of different length resulting in multipath phenomena. Multipath propagation and the irregular motion of the ionosphere distort signals, which have propagated via the ionosphere over long distances, both in amplitude and phase characteristics. This distortion sets limitations on the rate at which information can be transmitted in a communication system. The nature of some of these short-term variations is described as follows:

a. Multipath Time-Delay Difference

There are several reasons for the occurence of the multipath phenomena. Complicated hops of both low and high rays involving a different number of ionospheric and ground reflections, with or without intervening reflections from F_1 and E layers, are a major source of multipath long-time delay. Shorter time-delay differences associated with each propagation mode may be caused by scattering from irregularities along the propagation path and by differences in the velocity of propagation of the magnetoionic components.

Some measured results on HF circuits of the fixed and meteorological services are given in CCIR Report 203. Severe multipath effects are shown when frequencies below optimum are used.

The time-delay difference between the first and last signal components due to multipath is dependent upon path length and the ratio of operating frequency to MUF [Salaman, 1962] . Figure 1 shows the maximum expected time-delay difference as a function of transmission path length. Figure 2 provides information about the anticipated time-delay difference in relation to the path length and the Multipath Reduction Factor (MRF). The MRF is the ratio of the operating frequency to the highest of the classical MUF's for simple E, F_1, and F_2 modes. As an example, for a path of 2000 km and an operating frequency of 65% of the MUF, the time-delay difference would generally be less than 1 millisecond as shown in figure 2.

b. Fast Fading

The signal at a receiver is made up of many phasors which are varying randomly. The resultant of these phasors varies in amplitude with time and is described as signal fast fading. The distribution of amplitudes approximates the Rayleigh distribution when the wave arrives via several modes with approximately equal amplitude and varying phases. This situation exists in many, but not all, cases of ionospherically propagated signals involving several modes for transmissions of CW or a train of relatively long pulses. For the Rayleigh distributior, the fraction of time p(E) that the amplitude of the resultant field vector exceeds the value E is equal to $\exp(-E^2/E_0^2)$, where E_0 is the root-mean-square (rms) value of E.

The measured results on the amplitude distribution in the HF band are summarized in CCIR Report 266. The fading range, defined as the difference between the values of the signal level exceeded for 10% and 90% of the time, is in the range of 9.8 and 16.2 dB on the average. Note that, although the form of the distributions may differ from that of Rayleigh, this observed fading range is very close to the value of 13.4 dB expected for the Rayleigh distribution.

The fading characteristics of a signal show diurnal and seasonal variations and also depend upon path location and frequency. Signals which have propagated through the auroral zone may, at times, fade at rates of more than 20 Hz [Koch and Petrie, 1962]. Both shallow and very deep fadings are observed on such a path. During the evening in the equatorial region, fading rates of 0.7 and 0.1 Hz were observed at frequencies of 10 and 20 MHz, respectively, although these values are expected to fluctuate over a considerable range [CCIR Report 343].

When the bandwidth of the transmitted signal approaches or exceeds a certain value, frequency selective fading becomes predominant, i.e., all frequency components in the transmitted signal no longer fade simultaneously. The correlation bandwidth of the HF propagation medium, which is defined as the frequency spacing at which the correlation coefficient of the amplitudes of two carriers falls to 0.5, ranges from a few hundred Hz to a few kHz, and is inversely proportional to the multipath time delay difference between the first and last arriving multipath components [Auterman, 1962].

The amplitude of a signal varies in a different manner with changes in frequency, space, polarization, and time. Therefore, two measurements made on transmissions as these quantities are varied are correlated to a degree which is dependent upon the frequency, space, polarization, or time separation. The principle of diversity reception is based on the above fact.

c. Frequency Fluctuations

The instantaneous received carrier frequency fluctuates regardless of how stable the transmitter frequency is maintained. Long-term changes in frequency are relatively small, usually being less than 1 Hz, but short-term changes can be much greater and may be of the order of tens of Hz [Davies and Baker, 1966].

CCIR Report 111 gives a theoretical curve of the distribution of the deviation of the instantaneous frequency from the average frequency. The curve is based upon a narrow-band Gaussian noise model and is normalized with respect to the fading rate. Experimental measurements of frequency fluctuation made on a trans-auroral path showed greater deviations than the theoretical curve; in this case, the theoretical curve fits the experimental distribution found if the normalizing factor is 1.4 times the fading rate rather than the fading rate itself [Auterman, 1962].

Measurements were made on the distributions of the percent of time the frequency deviations exceeded certain values for various time duration on the same path [Auterman, 1962]. The results of the measurements showed a wide dispersion of data. Figure 3 shows the data for two extreme cases, one for maximum frequency deviation observed and the other for minimum.

CCIR Report 343 describes results observed in the equatorial region. Frequency fluctuations induced by ionospheric irregularities during the occurrence of the evening disturbances exhibited frequency changes on the order of 20 to 30 Hz for carrier frequencies of 10 and 20 MHz. The average value of frequency spreading observed in this region was of the order of 5 to 10 Hz.

d. Phase Fluctuations

In addition to the amplitude and frequency fluctuations of signals there are also phase fluctuations. Figure 4 shows a theoretical distribution of phase perturbation for a Rayleigh-fading CW signal in terms of the sampling interval and the fading rate. The curves in the figures are calculated by the method given by Koch and Beery [1962]. If the fading were not Rayleigh but due to both a strong specular component and other randomly varying components (Nakagami-Rice fading), the phase perturbations would be less than those shown in figure 4.

Phase perturbations measurements of the received signals between various length sampling intervals, ranging from 1 to 20 milliseconds, were carried out on a trans-auroral path by Koch and Beery [1962].

Figure 5 shows sample distributions of phase perturbations of the received CW carrier for various length sampling intervals. Figure 6 shows distributions of phase perturbations for different fading rates, at sampling intervals of 1 and 4.5 milliseconds. These measurements indicate an increase in the phase perturbation with an increase in the fading rate for longer sampling intervals, while a clear dependence upon the fading rate is not shown for shorter intervals. A measurement of the pulse-to-pulse phase stability of 1-millisecond pulses transmitted at intervals of 4 milliseconds over the same path showed no significant difference, for comparable fading rates, between pulse-to-pulse phase perturbations and those of CW signals. If pulse-to-pulse phase comparison of pulses short enough to isolate the various multipath components were made, it is likely that a greater degree of phase stability would exist than for CW signals.

Other measurements made on a path from Pirmasens, Germany, to Frederick, Maryland [deHaas, 1964], showed that phase fluctuations were a little less than the theoretical curves shown in figure 4. Measurements of the probability distributions of the phase differences between two CW signals spaced at 32.4 and 75.6 Hz with an averaging time of 92 milliseconds were also carried out on the same path [deHaas, 1964]. The results indicated that the probability that the phase difference exceeded 45° ranged from 0.025 to 1.4% and from 0.32 to 10% for the frequency spacings of 32.4 and 75.6 Hz, respectively.

Measurements of the autocorrelation function of the phase of a stable CW signal transmitted over a temperate latitude path have been made by David et al. [1965]. These measurements show that the correlation decreases to a value of 0.5 with a time spacing of approximately 1 second. The fading rate during these measurements was less than one fade per second. At higher fading rates one would expect less time spacing for the value to be reduced to 0.5. This same report shows measurements of the correlation of the phase of two CW signals as a function of their frequency spacing, which indicate that the correlation was 0.5 when the frequency spacing was approximately 280 Hz.

2.3. Radio Noise

Noise sources external to the HF communication system which may cause degradation of the system can generally be classified as atmospheric, cosmic, or man-made noise.

a. Atmospheric Noise

Atmospheric noise results from lightning discharges. It varies diurnally in accordance with thunderstorm activity and propagation conditions between the noise sources and the receiving point. Major atmospheric noise sources are located in equatorial regions of South America, Africa, and the East Indies. CCIR Report 322 contains world-wide noise maps and graphs of the statistical variation of atmospheric noise and its dependence on time and season. CCIR Recommendation 372 recommends that the Report be used until such time as further revision seems desirable.

Measurements of the amplitude probability distribution (APD) of the atmospheric noise made for wide ranges of bandwidth and frequency showed that all of the APD's had the same form and could be represented to a good degree of accuracy by a single mathematical description [Spaulding, 1966]. At low levels, the APD is Rayleigh; while at the impulsive high levels, it departs greatly from Rayleigh. If the entire APD is plotted on coordinates in such a way that the Rayleigh distribution plots as a straight line, then the distribution in the impulsive region will also plot as a straight line of greater slope. It has been further found that by giving the ratio of the rms voltage to average voltage, an APD sufficiently accurate for many purposes could be determined.

Measurements of the autocorrelation function of the instantaneous amplitude of atmospheric noise indicate that the noise amplitude is essentially uncorrelated for a time interval longer than 30 milliseconds [Spaulding, 1966].

b. Cosmic Noise

Cosmic noise, coming mainly from the galaxy, has the characteristics of thermal noise. While it may be seen between bursts of atmospheric noise on frequencies near the upper end of the HF band, it is generally of little importance, in non-polar regions, on most frequencies in the HF band. This in part is because that portion of the ionosphere, used to propagate a signal at a given frequency and angle, shields the earth from extra-terrestrial radiation coming in on that frequency and angle.

c. Man-Made Noise

Man-made noise may arise from a number of sources, such as power lines, industrial machines, diathermy machines, ignition systems, etc., and thus, its characteristics vary over a wide range of limits. In general, the level of man-made noise decreases with increasing frequency at a rate of approximately 28 dB for each decade of frequency [CCIR Report 258].

Measurements on man-made noise indicate that the APD's for man-made noise can be treated much as those for atmospheric noise have been, although the form of the complete APD may vary from that used for atmospheric noise [JTAC, 1966].

3. COMMON PROBLEMS IN HF IONOSPHERIC COMMUNICATION

3.1. Selection of Traffic Frequency

Since the effectiveness of HF ionospheric communication largely depends upon the traffic or working frequency, it is necessary to select the traffic frequency properly. Various techniques have been proposed and used. A comprehensive description covering the whole area is given by Davies [1965].

As a signal with a frequency above the MUF cannot be reflected by the ionosphere and as the ionospheric absorption decreases as the square of the traffic frequency, the prediction of the MUF is one of the factors of primary importance. Indices to be used for predicting the MUF are recommended in CCIR Recommendation 371.

Permanent predictions are those which describe the variations of the ionosphere over a complete solar cycle [Davies, 1965]. They are particularly useful for long-term frequency planning and communications equipment specifications. Such predictions have been issued by several countries. An International Working Group, established under CCIR Resolution 10-1, is now engaged in the production of a CCIR atlas of ionospheric characteristics which will allow users in all parts of the world to estimate the monthly median MUF for a particular requirement as a function of time of day, season, and level of solar activity.

A variety of ionospheric predictions are also issued monthly by laboratories in a number of different countries, usually 3 months or so in advance.

The monthly predicted value of MUF is the median value, and a signal with this frequency would be propagated 50% of the time only. It is customary to use a value of 0.85 of the monthly median, which is called the optimum traffic frequency (FOT). The FOT is not necessarily the frequency of maximum signal strength or minimum time dispersion.

The use of the FOT is based on the result of a statistical computation which shows, for a specific assumed distribution which normally agrees with observations, the FOT lies below the maximum frequency 90% of the time.

Another International Working Group, reorganized by CCIR Resolution 7-1, is engaged to establish a method of predicting sky-wave field strength and transmission loss [CCIR Recommendation 341] for an HF ionospheric path.

In order to select a proper traffic frequency in HF ionospheric communication, the prediction of only the MUF or the field strength is not sufficient but several other factors, such as SNR, signal-to-interference ratio, etc., must be taken into account. The Frequency Utilization Section of the ITSA currently makes predictions of the performance of HF ionospheric telecommunication systems over given paths, which include these factors. These predictions can be made monthly, for a period 3 months in advance. The theoretical basis for this kind of prediction is described by Lucas and Haydon [1966].

While monthly predictions so far described are valuable for planning purposes, the rigid scheduling of operations according to the predicted FOT neither represents the most efficient frequency utilization nor guarantees the most reliable transmission because of the statistical nature of the monthly predictions and possible ionospheric disturbances. Some more effective provision needs to be made for scheduling hour-to-hour frequency change. An adequate short-term prediction on an hour-to-hour basis, say, one day in advance, requires both current propagation observations and indices of trends to be obtainable from analyses of solar and magnetic observations. Information obtainable from back-scatter observations [CCIR Report 261-1] or oblique sounding [Hatton, 1961] in selected areas and over selected circuits may be very valuable for the short-term prediction. The Short-Term Ionospheric Prediction Research Section of the ITSA is establishing a technique for short-term predictions and its application to HF radio links. The Section is developing techniques to provide hourly predictions of MUF for 3 hours in advance, based on hourly ionospheric sounding data.

The ionosphere is subject to disturbances, such as (1) sudden ionospheric disturbances, (2) ionospheric storms, or (3) polar cap absorption events. These disturbances result in interruption of radio communications for periods lasting from a few minutes to several days. Forecasting of the probable occurrence of an ionospheric disturbance can be very useful, because, as soon as the warning is received, a communication operator may either transmit his essential messages before the circuit is blacked out, or take action for starting up various relay links or changing the operating frequency. Several radio forecasting centers in various parts of the world regularly issue forecasts of radio propagation conditions. Procedures of exchanging information for the preparation of short-term forecasts and of transmitting ionospheric disturbance warnings are given in CCIR Recommendation 313-1.

3.2. Siting and Antennas

A substantial treatment of the factors that should be considered in selecting a site for an HF communication facility was made by Utlaut [1962]. CCIR Recommendation 162-1 specifies minimum standards and economic standards for directional antennas in the fixed-service bands between 4 and 28 MHz, based upon the measured performance of typical rhombic antennas and typical antenna-arrays. CCIR Reports 106 and 107-1 summarize the experimental results on directional antennas. Application and design information for standard HF antennas is given by Jasik [1961].

Since long-distance HF communication is dependent on a variable ionosphere, a knowledge of the particular propagation path and frequency range is necessary as a prerequisite to siting and antenna design for a particular circuit. Information concerning angles of departure and arrival is necessary in order that the antenna system can be designed to have lobes at vertical angles which favor these angles of departure or arrival [Perlman, 1964].

Energy radiated from an antenna at an angle below the horizon is reflected from the ground and combines with energy radiated at higher angles from the antenna. The intensity of the reflected wave depends upon the reflection coefficient of the earth and may be very nearly as great as the direct signal for a moist loam soil. The phase relationship between the direct and reflected signals results in cancellation or reinforcement of the field radiated from the antenna at various vertical angles causing nulls and lobes in the vertical pattern. The height of the antenna above the earth, therefore, has a great effect on the vertical pattern of the antenna.

The topography of the area for a considerable distance in front of the antenna (the first Fresnel zone) is of great importance, since the contributions of reflected energy come from this area. Ideally this area should be very smooth and free from obstructions. Deviations from the ideal can be tolerated at a cost in performance. In many cases a sloping area in front of the antenna can be used to substantially reduce the antenna heights that might be required to achieve low angle radiation.

Radio transmitters located within several kilometers of a receiving station may create serious interference due to harmonics, keying transients, parasitic oscillations, or co-channel operations. Distant stations operating on frequencies within the pass band of the receiver may also cause interference, and such interference may enter a system via antenna side lobes as well as on the main lobe. Because of the great variability of radio interference from location to location and also from time to time, an on-site measurement is generally required in order to properly evaluate such interference.

Proper design of antennas can reduce the effects of multipath. In general the later arriving modes, corresponding to a larger number of hops, arrive at higher angles than the earlier arriving modes. Thus, an HF link, which will respond to a single reliable mode while rejecting other modes by means of a null or nulls in the antenna patterns, may reduce the effect of the time delay difference in received signals.

In some cases the deleterious effects of atmospheric and man-made noise and radio interference may also be reduced by careful antenna design which will minimize the strength of the disturbing signal.

Special configurations of antennas, such as the Wullenweber, billboard, log-periodic [Rumsey, 1957; DuHamel and Ore, 1958] , etc., are generally designed to meet specific requirements.

3.3. Diversity Operation

As described earlier the field strength of the received signal varies in a different manner with changes in space (receiving antenna location), polarization, frequency, and time. These characteristics can be utilized to reduce the deterimental effects of fading by diversity techniques, which function on the basis of the reception of two or more uncorrelated signals from the same source and combine, or select, them in an appropriate manner.

Of the various possible diversity techniques, i.e., space diversity, polarization diversity, frequency diversity, and time diversity, only space or polarization diversity can be recommended, because other techniques are wasteful of frequency spectrum utilization or transmission time.

CCIR Report 266 describes some results from both theoretical and experimental studies on the improvement achieved by space or polarization diversity, but the study is still being conducted under CCIR Study Programme 16A/ VI.

Several methods of combining the receiver outputs exist, such as (1) adding the pre-demodulation signals in an optimum ratio (proportional to the instantaneous signal-to-noise power ratio); (2) adding the post-demodulation signals in the same ratio as in (1); (3) equal gain combining of the post-demodulation signals; (4) post-demodulation switching to the strongest signal; or (5) numerous other techniques. No standards exist at this time for determining the specific type to be employed for a given system. It seems desirable that a new CCIR question on the standardization of the diversity technique be raised.

4. MODULATION TECHNIQUES FOR HIGH-SPEED DATA TRANSMISSION

4.1. Use of Standard Radiotelephone Channels

It is specified in Article 7 of the Radio Regulations [ITU, 1959] that the frequency necessary for the international exchange of synoptic meteorological information shall be selected from the band allocated to the fixed service. In the field of fixed-services HF communications, techniques as well as technical standards for radiotelephone communication by single-sideband (SSB) and independent-sideband (ISB) modulation have already been well established [CCIR Recommendations 335-1, 338-1, 339, 348-1, 349-1; CCIR Report 181]. As will be described later, it is not likely that high-speed data transmission in the HF band can satisfactorily be achieved by simply speeding up the keying rate of currently existing low-speed radiotelegraph. Therefore, it is recommended that high-speed (and also the higher part of medium-speed) data transmission be achieved using a standard radiotelephone channel of nominal 3-kHz bandwidth, which actually extends from 250 to 3000 Hz. By so doing, major parts of existing techniques and equipments for HF radiotelephone communications can be utilized for high-speed data transmission. Compatibility with telephone circuits is also desirable in practical operations.

Operating HF radiocommunication facilities for a single circuit cannot be as efficient as the operation of the facilities for commercial radio circuits, which are operated for many purposes on a time-sharing basis. In addition, commercial radio circuits are generally operated by administrations or recognized private organizations which have extensive knowledge and experience concerning HF radio propagation and practical operations of HF circuits. Therefore, it is recommended that commercial radio circuits be leased, wherever possible, in point-to-point systems unless high-quality HF radiocommunication facilities equivalent to those of commercial radio circuits already exirt at both terminals of a particular circuit.

4.2. Advantages of Frequency Multiplexing

Modulation techniques to be used for high-speed data transmission can be classified into two broad categories, i.e., serial modulation and frequency multiplexing.

Serial modulation is the simpler and more straightforward technique. It transmits the information serially in a single channel. This implies the use of very short signal elements; for example, the element length is 0.833 milliseconds in a binary system operating serially at a data signalling rate of 1200 bits/second. In ionospheric transmission, however, such short elements are subject to severe interference from multipath components, which can be delayed as much as several element lengths. For this reason, serial modulation should not be used for high-speed ionospheric modems.

Frequency multiplexing is a technique in which an authorized frequency slot is divided into a number of subchannels, the data is transformed from serial to parallel form, and each subchannel is operated at a lower data signalling rate, equal to the original rate divided by the number of subchannels. This technique allows each subchannel to be operated at a low modulation rate, and thereby provides elements long enough to avoid serious multipath degradation. Signal elements of at least twice the expected multipath delay difference are normally used in ionospheric transmissions.

The maximum number of subchannels, using frequency multiplexing, is limited by the frequency fluctuations of the propagated signal, to avoid mutual interference between subchannels. Frequency spacings of at least 25 or 50 Hz are generally required between any two frequencies chosen in the frequency slot.

4.3. Various Types of Possible Modems

As described above, an HF, high-speed data transmission system is essentially an aggregate of a number of narrow-band subchannels, closely spaced in frequency and operated individually at a low rate. Various types of modems are possible for these subchannels.

A sinusoidal wave can be uniquely specified by its amplitude, frequency, and phase, and, therefore, the information to be transmitted can be modulated onto either one of these three parameters. Corresponding to the three parameters, the modems to be used in the subchannels can be classified into three categories, i.e., amplitude modulation or on-off keying, frequency modulation or frequency shift keying (FSK), and phase modulation or phase shift keying (PSK).

a. On-Off Keying Modems

In a multiplex on-off keying modem a subcarrier frequency is assigned at the center of each subchannel. The digital information is transmitted by on-off keying of the unmodulated subcarriers.

b. FSK Modems

In a multiplex FSK modem a certain number of equally spaced frequencies f_0, f_1, ..., f_{n-1} are chosen in each subchannel, where n is the number of the chosen frequencies. A subcarrier is frequency-modulated or frequency-shifted in accordance with the digital information such that the frequency of the subcarrier is equal to f_i during a time interval in which the information content is equal to i. The data signalling rate is equal to $(\log_2 n)/T$ bits/second, where T is the element length. According to two different schemes of transmission, FSK modems can be classified into two categories, i.e., coherent FSK (CFSK) and non-coherent FSK (NCFSK).

A CFSK modem is one which utilizes both phase and frequency information of the subcarrier. In the modulator, the subcarrier is modulated to associate a predetermined phase with each frequency, f_i. In the demodulator, a phase reference is generated locally for each frequency f_i, and a coherent detector is provided for each of these frequencies. The detector which has the largest output is then selected as representing the transmitted information.

An NCFSK modem does not utilize such a phase reference. There are two kinds of demodulation methods for NCFSK modems. One is called discriminator method and uses a frequency discriminator, while the other is called single-source n-filter method (or matched filter method) and uses n band-pass filters and envelope detectors corresponding to the n frequencies.

c. PSK Modems

In a multiplex PSK modem a subcarrier frequency is assigned at the center of each subchannel. The subcarrier is phase-modulated or phase-shifted by the digital information so that the difference between the phase of the subcarrier φ and the reference phase φ_0 is equal to

$$\varphi - \varphi_0 = (2i + 1 - n)\,\pi/n, \quad (i = 0, 1, 2, \ldots, n - 1) \quad ,$$

where n is the number of different phases onto which the information is modulated. The data signalling rate is equal to $(\log_2 n)/T$ bits/second, where T is the element length. According to different transmission schemes with regard to the reference phase, PSK modems can be classified into four categories, i.e., constant-reference or coherent

PSK (CPSK), time-differential PSK (TDPSK), and two types of frequency-differential PSK (FDPSK) [deHaas, 1965].

A CPSK modem is one in which a subcarrier is phase-modulated relative to a constant phase reference and demodulated relative to a phase reference locally generated at the receiver.

A TDPSK modem is one in which both modulation and demodulation are referenced to the phase of the subcarrier during the previous signal element.

An FDPSK modem (Type 1) is one in which a subcarrier is phase-modulated relative to a constant phase reference and the phase reference is transmitted via additional unmodulated subcarriers closely spaced in frequency to the modulated subcarrier. Demodulation may be made relative to a single unmodulated subcarrier or to a "phantom" phase reference derived by interpolation from two unmodulated subcarriers between which the modulated subcarrier is situated.

Another FDPSK modem (Type 2) is one in which both modulation and demodulation of the (k + 1)st subcarrier are referenced to the phase of the kth subcarrier.

d. Preliminary Selection of More Favorable Modems for HF Ionospheric Paths

Although there are many types of possible modems for digital data transmissions as described above, we can, on a preliminary basis, select from these some of the more favorable high-speed modems for use over HF ionospheric paths.

As the amplitude of the signal propagated over ionospheric paths generally fluctuates to a considerable extent, the on-off keying of a sub-carrier is not suitable for automated high-speed data transmission over the ionosphere. The on-off keying modems can thus be used only for low-speed telegraphy and are omitted from our considerations.

As the phase of the signal propagated over ionospheric paths also fluctuates to a considerable extent, it is almost impossible to obtain low error rate when using a locally generated phase reference. This applies to both FSK and PSK modems. For this reason, both the CFSK and CPSK modems can be dropped from our considerations.

It is, therefore, concluded that our further discussions on modems can be confined to the NCFSK, TDPSK, and the two types of FDPSK modems.

4.4. Practical Limitations on the Data Signalling Rate

One of the objectives of this study is to determine appropriate modems which can provide high-speed data transmission with a data signalling rate of either 1200, 2400, or 4800 bits/second within a standard radiotelephone channel extending from 250 to 3000 Hz. Although it is theoretically possible to accommodate any high-rate channel in a given band, there are practical limitations on the data signalling rate because of several reasons.

In order to discuss these limitations we shall introduce the following symbols:

B = overall bandwidth (Hz),

b = bandwidth of each subchannel (Hz),

N = number of information subchannels,

n = number of frequencies in a subchannel for FSK, and number of phases in a subchannel for PSK,

R = overall data signalling rate (bits/second),

r = data signalling rate in a subchannel (bits/second),

r_m = modulation rate (bauds),

T = total element length (second),

T_a = usable information element length (second), and

T_g = guard time in each element (second).

Then , the following relations hold:

$$B = N \cdot b \cdot c,$$

$$R = N \cdot r,$$

$$r = (\log_2 n) \cdot r_m,$$

$$r_m = 1/T,$$

$$T = T_a + T_g, \text{ and}$$

$$b \geq 1/T_a,$$

where c is a constant, not less than unity, depending upon the type of modems and the method of multiplexing.

a. NCFSK Modems

Since no phase information is transmitted in NCFSK modems, the constant c is equal to $(N + 1)/N$ or 1 depending upon whether an additional subchannel is used for synchronization purpose or not. In any case, the value of c is essentially equal to 1 in this modem because N is generally much greater than 1. Therefore, the relation between the bandwidth and the data signalling rate does not essentially depend on the method of multiplexing.

When a single-source n-filter (or matched filter) method is used for demodulation, the minimum value of subchannel bandwidth b required for the data signalling rate r is equal to n/T_a. Therefore, we obtain

$$b/r \geq (T/T_a) \cdot [n/(\log_2 n)] .$$

The value of the factor $n/(\log_2 n)$ is equal to 2, 2, 2.667, and 4 for the value of n equal to 2, 4, 8, and 16, respectively. From these relations, even if no guard time is used, a data signalling rate of at most 1200 bits/second is permitted for a total bandwidth of 2750 Hz with $n = 2$ or 4 (i.e., $b/r \cong 2$, thus $R \cong B/2$).

When the discriminator method is used in the demodulator, the situation is slightly different. There is no clear cutoff in the required bandwidth b, and CCIR Recommendation 436 recommends the use of a b/r ratio of as low as 1.7 in binary systems (n = 2) with the modulation index of about 0.8. (Modulation index of a binary FSK system is defined as the ratio of the difference between the frequency f_0 or f_1 and the center frequency of the subchannel to the reciprocal of twice the element length T.) This would permit a data signalling rate up to 1600 bits/second in a 2750-Hz bandwidth. The data signalling rate of 2400 bits/second may also be possible with modulation index of about 0.5, but higher rates cannot be accommodated in binary modems, because b/r should always be greater than 1. A data signalling rate higher than 2400 bits/second is theoretically possible for a quaternary system (n = 4) with the minimum subchannel bandwidth 1/T, but this is not recommended because the required SNR is very high for this type of modem. It should be noted that a wider bandwidth is required for values of n greater than 4 to obtain equivalent performance with this type of modem. Therefore, the use of a data signalling rate higher than 2400 bits/second as well as the value of n greater than 4 may not be recommended in this case.

In summary NCFSK modems may be used for data signalling rates of 1200 and 2400 bits/second with 2 or 4 frequencies in each subchannel (i.e., binary or quaternary), and the data signalling rate of 2400 bits/second is available only when the discriminator method is used in the demodulator.

b. TDPSK Modems

As no unmodulated subcarriers are necessary to transmit phase references, the value of c is equal or close to 1 in TDPSK modems as in NCFSK modems.

In order to minimize inter-subchannel interference (crosstalk), TDPSK modems are generally designed in such a way that the subchannel signals are orthogonal to each other, i.e., all the subcarrier frequencies are integral multiples of the reciprocal of the integration time (usable information element length) T_a. This leads to the relation that

$$b = 1/T_a \ ,$$

and we obtain

$$b/r = (T/T_a)/(\log_2 n)$$

The value of b/r decreases monotonically as n increases. Its maximum value is T/T_a when n = 2. If no guard time were required, therefore, the data signalling rates of 2400 and 4800 bits/second would be available in a standard 2750-Hz radiotelephone channel with n = 2 (binary keying) and n = 4 (quaternary keying), respectively.

In practical TDPSK modems, however, a guard time of at least a few milliseconds is required to combat the effect of multipath time delay differences, and this requires a wider bandwidth by a factor $T/T_a = (T_a + T_g)/T_a$. In order to minimize the undesirable increase in bandwidth, we must make T_a long enough, say 10 times T_g or longer. But long elements suffer from the effect of phase fluctuation, and the signal element should be kept as short as possible in order to keep the effect of phase fluctuation to a minimum. Because of the two contradictory requirements on the design of TDPSK modems, only data signalling rates of about 1500 and 3000 bits/second are available in practice with n = 2 (binary keying) and n = 4 (quaternary keying), respectively.

c. FDPSK Modems (Type 1)

In this type of modem a number of unmodulated subcarriers are necessary to transmit phase references of modulated subcarriers. The value of c depends on the arrangement of the unmodulated subcarriers as well as the number of the modulated subcarriers. If the number of modulated subcarriers arranged between a pair of unmodulated subcarriers is denoted by M, the number of unmodulated subcarriers is equal to N/M + 1, and the value of c is given by

$$c = (N + N/M + 1)/N$$

$$= 1 + 1/M + 1/N$$

In order to avoid the multipath effect, N should not be less than 10. The number M generally should not be greater than 5, because the frequency spacing of the unmodulated subcarriers should not be wider than 100 or 150 Hz to retain sufficient correlation of phase fluctuations, while the frequency spacing of the modulated subcarriers should not be less than 20 or 25 Hz to avoid the deleterious effect of frequency fluctuations. Therefore, the range of the value of c is restricted in this type of modem and is given by

$$2.1 \geq c \geq 1.2$$

From the requirement of orthogonality, we obtain

$$b/r = (T/T_a)/(\log_2 n)$$

as in the TDPSK modems. Since T_a can be as long as 40 or 50 milliseconds in this type of modem, the ratio T/T_a can be 1.1 or less with a guard time of a few milliseconds.

From these relations, the maximum data signalling rates with n = 2 and 4 available for this type of modems in a standard radiotelephone channel are 2000 and 4000 bits/second, respectively.

d. FDPSK Modems (Type 2)

In this type of modem unmodulated subcarriers are not necessary to transmit phase references, and the value of c can be equal or very close to 1. The discussion on the ratios b/r and T/T_a given to Type 1 of FDPSK modem can equally apply to this type of modem. Therefore, there is no problem for this type of modem to accommodate the data signalling rates of 2400 and 4800 bits/second in a standard radiotelephone channel with n = 2 (binary keying) and n = 4 (quaternary keying), respectively.

4.5. Basic Performance Characteristics of the Modems

Although signals propagated via the ionosphere suffer a number of unique perturbations due to short-term propagation effects not normally present in wire-line systems, there is often a tendency to theoretically analyze the performances of the modems for conditions without such perturbations (i.e., for conditions of non-fading or slow flat-fading signals without frequency or phase fluctuations). The results of these analyses are not only helpful in order to get a general idea on the performances of the modems, but also very important in practice because, if the difficulties caused by such perturbations could be overcome by appropriate design technique, they would give the ultimate performances of the modems. There are many studies in this field [Reiger, 1953; Montgomery, 1954; Lawton 1958; Smith, 1962; Shepelavey, 1963; Spaulding, 1964; Pelchat, 1964; Conda, 1965; Bello, 1965; White, 1966; Spaulding, 1966] . CCIR Report 195 gives some methods of predicting performance of telegraph systems in terms of bandwidth and SNR.

It is convenient to represent the theoretical relation between binary error rate and SNR by drawing a curve for each modem in a graph with the SNR in decibels and the binary error rate in a logarithmic scale as an abscissa and ordinate, respectively. (In this report SNR implies the ratio of total signal power to noise power contained in the nominal 3-kHz bandwidth.) From the results of the above studies we can make the following statements on the shape of the curves:

(1) For binary keying modems, the shape of the curve depends only on the amplitude distribution function of the fading signal and the noise, and does not depend on the type of modems, insofar as the four modems selected here are concerned;

(2) For quaternary NCFSK modems, the shape of the curve is different from that for binary keying modems. But the shapes of the curves for binary and quaternary NCFSK modems are quite similar in the range of lower error rate, say 0.01 or less, which is of practical importance; and

(3) For quaternary TDPSK and FDPSK modems, the shape of the curve is the same as for binary modems.

For the above reasons, the curves for one binary modem only will be depicted in this report.

The theoretical error rates in a binary NCFSK system are shown in figure 7 for non-fading and Rayleigh-fading signals and for Gaussian noise and atmospheric noise with an rms-to-average ratio V_d of 6 dB, which is the highest value likely to be of interest in HF ionospheric communications. It can be observed from the figure that atmospheric noise is much more harmful than Gaussian noise at the higher SNR, while Gaussian noise is more harmful for the lower SNR. It is also clear from the figure that, when the signal is Rayleigh fading, Gaussian noise is more harmful at all SNR.

To apply the curves in figure 7 to each of the modems, some comments are necessary. These comments will be given for each modem separately.

a. NCFSK Modems

The curves in figure 7 are applicable to a binary NCFSK modem using either the discriminator method or the single-source two-filter method of demodulation, as long as the modulation index is not less than unity.

The curves in the figure are based on the observation that errors do not occur as long as the signal amplitude exceeds the noise amplitude and that the error rate is one-half the probability that the noise amplitude exceeds the signal amplitude [Montgomery, 1954]. This is true when the modulation index is at least unity. Therefore, figure 7 is applicable when a data signalling rate of 1200 bits/second is used in a standard radiotelephone channel, because the modulation index can be equal to or greater than unity in this case.

When the modulation index is less than unity, on the other hand, there are chances that errors can occur even if the signal amplitude exceeds the noise amplitude. For a given value of modulation index of less than unity, errors can occur unless the signal amplitude exceeds $\operatorname{cosec}(\pi d/2)$ times the noise amplitude, where d denotes the modulation index. To use a data signalling rate of 2400 bits/second for a binary NCFSK modem in a standard radiotelephone channel, the modulation index should be in the neighborhood of 0.5, and it is expected that the required SNR is considerably greater than that shown in the figure. Smith [1962] showed that the required SNR is minimum for d = 0.7 and CCIR Recommendation 436 recommends the use of d = 0.8, but this does not mean that an NCFSK modem works well without a considerable sacrifice in the required SNR at the modulation index of 0.5. It is shown that the spectrum of the modulated signal wave for d = 0.5 is very different from that for d = 0.7 or 0.8 [Pelchat, 1964].

For a quaternary NCFSK modem using single-source four-filter method of demodulation and operating at a data signalling rate of 1200 bits/second, the required SNR is about 2 dB less than that shown in figure 7 for binary error rates of interest, say 0.01 or less. For a quaternary modem using discriminator method and operating at the same data signalling rate, the required SNR is expected to fall between the above two.

There are no data which are applicable to a quaternary modem operating at a data signalling rate of 2400 bits/second in a standard radiotelephone channel, but it is anticipated that the required SNR will be greater than that shown in figure 7.

b. TDPSK Modems

The required SNR for a binary TDPSK modem is the same as shown in figure 7. This applies to a binary modem operating at a data signalling rate of about 1500 bits/second in a standard radiotelephone channel.

For a quaternary TDPSK modem the required SNR is 3 dB greater than that for a binary TDPSK modem. This applies to a quaternary modem operating at a data signalling rate of about 3000 bits/second.

c. FDPSK Modems (Type 1)

The required SNR for a binary FDPSK modem of this type is approximately the same as that shown in figure 7. The phase fluctuation due to noise in the interpolated phase reference would be smaller than that in a subcarrier itself, but additional power is contained in the unmodulated subcarriers. The difference in the required SNR between NCFSK and this modem depends on the arrangement of unmodulated subcarriers and does not exceed 3 dB in any case. This applies to a binary modem operating at a data signalling rate of about 2000 bits/second in a standard radiotelephone channel.

For a quaternary FDPSK modem of this type the required SNR is approximately 2 dB greater than that for a binary FDPSK modem of this type. This applies to a quaternary modem operating at a data signalling rate of about 4000 bits/second.

d. FDPSK Modems (Type 2)

The required SNR for a binary FDPSK modem of this type is the same as that shown in figure 7. This applies to a binary modem which operates at a data signalling rate of 2400 bits/second in a standard radiotelephone channel.

For a quaternary FDPSK modem of this type the required SNR is 3 dB greater than that for a binary FDPSK modem of this type. This applies to a quaternary modem operating at a data signalling rate of 4800 bits/second.

4.6. Effects of Propagation Factors on the Performance of the Modems

As described earlier, signals propagated via the ionosphere suffer a number of unique perturbations due to short-term propagation factors, such as multipath, fast fading, frequency fluctuations, or phase fluctuations The technique of frequency multiplexing is required for HF high-speed modems to avoid the deleterious effect of multipath propagation. Four types of modems have been selected out of many possible modems by taking into account some of the propagation factors. It is necessary to discuss in more detail how the propagation factors affect the performance of each selected modem and to find out how the performance can be optimized against the perturbations due to the propagation factors.

Signal elements of at least twice the expected multipath delay difference are required in all the selected types of HF high-speed modems. This poses a lower bound on the element length. On the other hand, frequency spacings between two adjacently chosen frequencies should be at least twice the expected frequency fluctuations of the received signal. This poses an upper bound on the element length, because the element length is equal or close to the reciprocal of the frequency spacing (except for the 2400-bits/second NCFSK modem for which the element length is equal to or less than one-half of the reciprocal of the frequency spacing). The restriction due to multipath and frequency fluctuation is more severe for a 2400-bits/second NCFSK modem than other selected modems.

In addition to the above restrictions, common to all the selected modems, the maximum element length for a TDPSK modem is further limited by the phase fluctuations, and the minimum element length for an FDPSK modem is limited by the correlation bandwidth of the phase fluctuations.

Equivalent statements to the preceding paragraphs can be made in a different terminology. The correlation bandwidth of the propagation medium is inversely proportional to the multipath time delay difference, and both the frequency and the phase fluctuations are proportional to the average fading rate or the bandwidth of the fading spectrum. Therefore, the modulation rate, which is the reciprocal of the element length, is limited by the correlation bandwidth and the fading bandwidth of the propagation medium at the upper and the lower bounds, respectively.

To achieve the minimum error rate dictated by SNR considerations, it is necessary to satisfy all the restrictions described in the above. But this is generally not the case in practical HF media. When the restrictions are not satisfied, there exists an irreducible error probability, beyond which one cannot reduce the error probability by increasing the SNR. Bello and Nelin [1962, 1963a, 1963b, 1964] have examined this problem in detail and derived results applicable to NCFSK and TDPSK systems. The results of these studies are expressed in terms of fading bandwidth and correlation bandwidth. The fading bandwidth is defined here as the frequency at which the fading power spectrum drops to $1/e = 0.36788$ of its maximum value, while the correlation bandwidth is defined as the frequency spacing at which the correlation coefficient of the amplitudes of two carriers drops to $1/e$ of its maximum value.

Figure 8 shows the error probabilities corresponding to the SNR of 27 dB and infinity in a binary NCFSK system with a matched-filter demodulator as a function of the normalized data signalling rate with no diversity, and figure 9 shows the same probabilities with dual diversity, both obtained by Bello and Nelin [1963b, 1964]. It is interesting that, for a given fading bandwidth and correlation bandwidth, there exists an optimum data signalling rate which will yield the minimum irreducible probability of error.

In the case of the TDPSK system, the curves of irreducible error probability were derived for two specific cases, also by Bello and Nelin [1962, 1963a]. In the first case it is assumed that the correlation bandwidth is sufficiently wide to have no effect and that the errors are contributed by the effects of time-selective fading (fast fading). The results of this analysis are presented in figure 10. In the second case, it is assumed that the time-selective fading is sufficiently slow to have no effect and that the errors are contributed by the effects of frequency-selective fading. The results of this analysis are presented in figure 11. Similar curves for the NCFSK system are also plotted in figures 10 and 11 for comparison purposes. It is evident from figures 10 and 11 that the TDPSK system is more sensitive to the effects of both time-selective and frequency-selective fading than the NCFSK system.

The reason that the TDPSK system is more sensitive than the NCFSK system might be interpreted as follows: the restriction on the maximum element length posed by the phase fluctuation, peculiar in the TDPSK systems, is more severe than that posed by the frequency fluctuation, common to the two systems. An example of this can be illustrated from the statistical data presented in figures 3 and 5. Figure 3 indicates that, for the element lengths of 10 and 20 milliseconds on a trans-auroral path at a fading rate of 6 Hz, the percentages of time that the frequency deviated more than 50 and 25 Hz (i.e., one-half of the orthogonal frequency spacings) for time intervals of 5 and 10 milliseconds (i.e., one-half of the element lengths) were 0.25 and 0.7%, respectively. Figure 5 indicates that, on the same path at a comparable fading rate of 7 Hz, the element lengths at which the phase perturbation exceeded 90° for 0.25 and 0.7% of the time were 3.7 and 6.3 milliseconds, respectively.

Unfortunately, analyses have not yet been made on the FDPSK systems. As described earlier, there is a restriction on the minimum element length (or the maximum frequency spacing) posed by the correlation bandwidth of the phase fluctuation in an FDPSK system in addition to the one posed by the multipath time delay difference, applicable to all selected modems. But the phase fluctuation is usually well correlated over a bandwidth of 100 Hz or wider and the minimum element length will be around 10 milliseconds, equal to what is required by the multipath time delay difference. Therefore, it might be concluded that the sensitivity of the FDPSK systems to the time-selective and frequency-selective fadings will be the same as that of the NCFSK system, because the additional restriction on the minimum element length in the FDPSK system posed by the correlation bandwidth of the phase fluctuation is not more severe than that posed by the multipath time delay difference, which is common to the two systems.

4.7. Examples of Practical HF Modems

In recent years, a number of high-speed HF modems have been developed. The main features of some typical modems are described here:

a. AN/FGC-29

This is a typical binary NCFSK modem, and is normally used for the transmission of telegraph, teleprinter, or telemetering signals over 16 parallel, FSK subchannels. It is capable of transmitting high-speed digital data by combining with a suitable serial-to-parallel converter such as Rixon Type DD-1003 Sepath System.

It has 16 subchannels the center frequencies of which are separated by 170 Hz, beginning at 425 Hz and ending at 2975 Hz. The modulation rate is 75 bauds, and the frequency shift is ±42.5 Hz. Therefore, the modulation index is equal to 1.13. The overall data signalling rate is 1200 bits/second.

The receiving terminal of this modem provides dual diversity of a ratio-squaring combining principle on an individual subchannel basis. Discriminator method is used for demodulation.

b. AN/FGC-61A

This is another typical binary NCFSK modem, similar to AN/FGC-29. It has 16 subchannels, the center frequencies of which are the same as in AN/FGC-29. The frequency shift is equal to ±42.5 Hz, which is again the same as in AN/FGC-29. Modulation rate can be as high as 90 bauds, but is normally 75 bauds. The overall data signalling rate is equal to 1200 bits/second at its normal operation, and it can be 1440 bits/second at its maximum operation.

At the receiving terminal, diversity combining on a switched controlled (selection) basis is performed for each subchannel. Discriminator method is used for demodulation.

c. Telesignal MODEL 5000 High Capacity Data System

This is also a binary NCFSK modem. It has 32 subchannels, the center frequencies of which are separated by 85 Hz, beginning at 340 Hz and ending at 2975 Hz. Modulation rate is 75 bauds and frequency shift is ±30 Hz. Therefore, modulation index is 0.8, and the overall data signalling rate is 2400 bits/second.

As an additional optional module a diversity comparator can be equipped in this modem, which is a repackaged version of Model 110 Dual Diversity Comparator. Discriminator method is used for demodulation.

d. Collins Radio KINEPLEX Modems

Kineplex is a well-known example of the TDPSK technique. There are a number of versions, and the major characteristics of some typical modems are listed in table 2. A quaternary (4-phase) modulation is used to accommodate two channels in each data tone and, when three channels are accommodated in a data tone, amplitude modulation (AM) is used for the third channel. As indicated in the table, orthogonal signalling is employed to minimize the effect of inter-subchannel interference (cross-talk), i.e., the channel spacing is equal to the reciprocal of the usable information element length.

Table 2. Major characteristics of various Kineplex modems.

Modem	No. of tones	Channel spacing (Hz)	Element length (ms)			Data rate (b/s)	
			Total length	Info. time	Guard time	2 ch/tone	3 ch/tone
TE-202	20	110	13.33	9.09	4.24	3000	----
TE-212D	4	440	3.33	2.27	1.06	2400	----
TE-216A-4	4	440	3.33	2.27	1.06	2400	3600
TE-216A-8	8	220	6.67	4.55	2.12	2400	3600
TE-216A-20	20	110	13.33	9.09	4.24	3000	4500
TE-216D-16D	16	110	13.33	9.09	4.24	2400	----

Dual diversity reception with post-detection combining is provided for each subchannel (data tone).

e. Hughes Aircraft HC-273

This is another TDPSK modem using a quaternary (4-phase) modulation. It has 12 tones with a uniform spacing of 200 Hz. Element length is 10 milliseconds and no guard time is provided. Therefore, the modulation rate is 100 bauds, and the overall data signalling rate is 2400 bits/second. In order that a band-pass filter can be used for each subchannel and automatic gain control (AGC) can be applied separately, this modem uses a wider subchannel spacing which is equal to twice the orthogonal spacing at a sacrifice in the data signalling rate. A diversity combiner of ratio-squaring type is provided for each subchannel.

f. General Dynamics/Electronics DEFT/SC-302

This is a typical FDPSK modem of Type 1. It has 22 unmodulated subcarriers (phase reference tones) with a uniform spacing of 125 Hz distributed throughout the baseband from 370 to 3000 Hz. Although there are twenty-one 125-Hz slots, each of which contains two modulated subcarrier (data tone) pairs, two of these tone pair positions are occupied by synchronizing tones. Therefore, there are 40 data tone pairs or 80 data tones, and the spacing between two adjacent tones (either data tone or phase reference tone) is 25 Hz. The element length is 40 milliseconds, which meets the requirement of orthogonality. As no guard time is provided, modulation rate is 25 bauds.

A quaternary (4-phase) modulation is used for the data tones, but only 8 of 16 possible coding combinations for each data tone pair are used and only 3 bits of information data are coded on a data tone pair by a special encoding and decoding technique. Therefore, the data signalling rate for each data tone pair is 75 bits/second, and the overall data signalling rate is 3000 bits/second. Note that, actually, 4 bits could be encoded on a data tone pair and the overall data signalling rate of 4000 bits/second could be used at a sacrifice of approximately 2 dB in the required SNR.

This modem is equipped for dual diversity employing equal-gain post-detection combining on an individual tone basis.

g. General Dynamics/Electronics ANDEFT/SC-320

This is a typical FDPSK modem of Type 2. The baseband spectrum of this modem contains 66 tones distributed from 400 to 3000 Hz with equal, orthogonal spacings of 40 Hz. This spectrum is functionally separable into halves. Each half consists of 32 tones carrying FDPSK-encoded data plus an additional tone serving as the "first-channel" phase reference and providing a means of receiver symbol synchronization. The usable information element length (detection interval) is 25 milliseconds and an additional 1.667-millisecond guard time between successive symbols is used; thus, the modulation rate is 37.5 bauds. This equipment provides data signalling rates of 4800 and 2400 bits/second with a quaternary (4-phase) and binary (2-phase) modulation, respectively.

This modem is equipped for dual diversity reception with equal-gain post-detection combining on an individual tone basis. In addition to the dual diversity, combinations of 4-phase or 2-phase modulation and in-band frequency diversity are also offered to provide data signalling rates of 2400, 1200, and 600 bits/second.

h. Other Modems

There are several other modems, e.g., Philco TSEC/HN-3, Robertshaw AN/FGC-75(V), General Atronics KATHRYN S-3000X, Cardion Electronics ADAPTICOM, etc. Two modems, the TSEC/HN-3 and the AN/FGC-75(V), use a TDPSK technique. The KATHRYN modem employs a special modulation technique which may be categorized as time/frequency differential PSK technique [Zimmerman and Kirsch, 1965] . The ADAPTICOM modem employs adaptive dispersion networks at the receiver so as to actually make use of the multipath structure of the ionospheric channel [DiToro et al., 1965] . However, these modems are not further considered in the present study because of either of the following reasons:

(1) a too high level of sophistication and consequent equipment complexity for the WWW application; and

(2) insufficient test data available to adequately predict actual performance characteristics.

4.8. Comparison Tests of Modems over HF Circuits

Some tests have been carried out in order to compare various modems and evaluate their performance over HF ionospheric circuits. Procedures and results of these tests will be reviewed:

a. Comparison of Various TDPSK Modems

A comparison test program of the performance of various TDPSK modems was carried out over an approximately 5000-km HF ionospheric path from Londonderry, Ireland, to Cheltenham, Md., during the period from October 1963 to December 1963 [DECO, 1964; Beach, 1965] . The modems tested included Collins KINEPLEX TE-202, TE-212D, and Hughes Aircraft HC-273. Digital information of 2400 bits/second generated by a pseudo-random pattern generator (Frederick Model 600) was transmitted simultaneously by two modems having equal modem output levels in the two 3-kHz radiotelephone channels nearest to the transmitter carrier frequency. Both transmitter and receiver had a frequency stability of at least 1 x 10^{-8} per day, and dual space diversity was used for the test.

The data indicated that the error rates in TE-202 and HC-273 were close to theoretical bounds calculated on the assumption of slow, flat fading signal and Gaussian noise. The TE-212D modem did not perform as closely to the theoretical bounds as the TE-202 and HC-273. The greater number of errors observed in the TE-212D can probably be attributed to intersymbol interference due to the short elements of 3.33 milliseconds.

b. Comparison of Various Types of Modems

A comparison test program of the performance of various type of modems was carried out over a 12700-km HF ionospheric path from Pretoria, South Africa, to Riverhead, Long Island, N.Y., during two 30-day periods, which included the month of April 1964 and the period from June 15 to July 14, 1964 [Greim et al., 1965; CCIR Report 346]. The modems tested included an NCFSK modem (AN/FGC-61A), a TDPSK modem (KINEPLEX TE-202), and an FDPSK modem of Type 1 (DEFT SC-302). The test was conducted on an equal energy per bit basis. Whenever possible, two modem systems were run simultaneously in the two 3-kHz slots on either side of the carrier, with periodic sideband switching to average out any systematic channel inequalities.

From the test data for parallel runs, the following deductions were drawn:

(1) the FDPSK modem performed at least as well as, and tended to be somewhat better than, the TDPSK modem;

(2) when the NCFSK modem ran at a binary error rate between 10^{-4} and 10^{-2}, the FDPSK was shown to be superior to the NCFSK modem; and

(3) no decision could be made concerning the advantage between the NCFSK and TDPSK, because of the small sample size obtained.

4.9. Recommended Modems

So far we have (1) preliminarily selected four types of modems, i.e., NCFSK, TDPSK, and two types of FDPSK modems, for high-speed data transmission in a standard radiotelephone channel over HF ionospheric paths, (2) discussed the data signalling rate and the error performance of the selected modems, and (3) described some typical modems and their comparison tests. The results of the study will be summarized, and some recommendations will be made on the selection of proper modems.

As indicated, the main difference in the capability among various modems lies in the different data signalling rate which can be accommodated in a standard radiotelephone channel. It is rather surprising that, if each modem is properly designed and operated, the total transmitter power required for each modem system to achieve an equal error rate in an equal bandwidth does not differ very much under normal propagation conditions.

A binary NCFSK modem utilizes a well-established technique, and a standard subchannel arrangement on HF radio circuit is recommended in CCIR Recommendation 436. The only disadvantage of the modem is its low data signalling rate. The data signalling rate can be as high as 2400 bits/second, at a sacrifice of a considerable amount in the required transmitter power, but is usually limited to 1200 or 1500 bits/second.

The use of quaternary (4-frequency) modulation in NCFSK modems can reduce the required transmitter power by 2 dB in 1200-bits/second system, but it cannot improve the data signalling capability in a given bandwidth. Therefore, the use of this technique is a trivial matter for our present purpose.

The TDPSK technique is not a new one and a number of modems are available in the market. But it should be noted that TDPSK modems are more vulnerable against unfavorable propagation conditions and more difficult to be properly designed than NCFSK and FDPSK modems. Therefore, regardless of the potential capability of TDPSK technique to handle a high data signalling rate, the maximum data signalling rate of a TDPSK modem available on HF ionospheric circuits is limited to 2400 or 3000 bits/second with the use of quaternary (4-phase) modulation.

The FDPSK modem of Type 1 appears superior to NCFSK and TDPSK modems in the data signalling capability with an equal or better error performance. It can handle a data signalling rate of 4000 bits/second at an error rate equal to or less than that of the other modems. But this modem technique is in an intermediate stage of technical development, and should not be considered to be a final version. The manufacturer of this modem was not quite satisfied with some aspects of this modem and has developed the FDPSK modem of Type 2, which can handle a data signalling rate of 4800 bits/second without any sacrifice.

Unfortunately, no data are available at the present time concerning the performance of FDPSK modems of Type 2 over HF ionospheric paths. But the principle of the FDPSK technique has already been tested by Type 1 and shown to be superior to other techniques, and there is no additional restriction due to propagation factors in Type 2 compared with Type 1. Therefore, it can be expected that the FDPSK modem of Type 2 performs equally well as Type 1.

As will be discussed later, more elaborate procedures of error control should be used on a radio circuit than on a metallic circuit, and it is anticipated that approximately the same number of parity check bits as the number of information bits should be used. For the metallic circuit, on the contrary, an error control procedure using 260 information bits and 12 to 16 parity check bits has already been recommended [Thompson, 1966], and, with this error control procedure, a data signalling rate of 2400 bits/second has been recommended for the metallic circuit [Wüsthoff, 1966].

Therefore, when the same information transmission rate is required on a radio circuit as on a metallic circuit, the data signalling rate of the HF modem must be 4800 bits/second. This high rate in a standard radiotelephone channel can be achieved only by the FDPSK modem of Type 2, and the use of this modem is recommended in this case.

When information transmission rates of only 1200 and 600 bits/second are required, the data signalling rate can be 2400 and 1200 bits/second, and a TDPSK modem and an NCFSK modem can be recommended, respectively. Of course, the FDPSK modem of Type 2 can be used in these cases with a better performance than TDPSK and NCFSK modems, but the price of the former is appreciably higher than that of the latter two at the present. As the use of TDPSK or NCFSK modem for the case of lower information transmission rates is recommended only for economical reasons, it should be limited to such a circuit for which the necessity of increasing the information transmission rate is not anticipated in the near future.

5. ERROR CONTROL FOR HIGH-SPEED DATA TRANSMISSION

5.1. Use of an Error Control System

Experience has shown that a sufficiently low binary error rate, say 10^{-5} or lower, cannot always be achieved in high-speed data transmissions on HF circuits without proper error control techniques. Also, the performance is poorer on HF circuits than on metallic (cable or land-line) circuits as far as raw error rates are concerned. Therefore, a more elaborate error control system should be used on HF circuits than the one recommended by Thompson [1966] on metallic circuits.

Error control coding functions on the basis of redundant digits (i.e., parity check digits) which are introduced in the data streams. It can be forward acting (one-way), feedback (two-way), or one of many more complicated network arrangements. The coding can be fixed, time variant and/or adaptive, or even probabilistic. Typically, the implementation involves a device at each terminal: an encoder at the transmitter, a decoder at the receiver, or a more elaborate data processor in case of joint operation. The decoder is usually the more complicated and expensive of the two. Because of randomly varying delays, some schemes, such as sequential decoding, detect and report, as well as others, may require considerable buffer storage to avoid overflow and loss of data.

The system can be either on a subchannel-by-subchannel basis or on a serial-data-stream basis. However, the error control system should be a part of the data terminal equipment and not of the data communication channel [Thompson, 1966]. In addition, all modern high-speed HF modems except NCFSK include serial-to-parallel converters in themselves. Therefore, the subchannel-by-subchannel method can be dropped from our further consideration.

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There are various error control techniques which are theoretically applicable to high-speed data transmission on HF circuits. According to different error-correction schemes, they can be classified into the following categories:

(1) forward (one-way) error-correction system without a return circuit;

(2) error-detection and retransmission system with a return circuit; and

(3) combination of the above two.

Each system has its advantages and disadvantages, and will be described in more detail separately, after briefly reviewing the theoretical background.

5.2. Theoretical Background

Coding theory abounds in coding schemes of tremendous variation. Even several years ago, the number of known code classes was quite large [Peterson and Massey, 1963], and is still growing. A recent clear account on the theoretical point of view for error control possibilities is available [Gallager, 1965]. CCIR Report 196-1 also summarizes results of many studies in this field.

While theory has been progressing, application of coding to real channels has been slow and painful. There has been no flood of results. This is particularly true for coding applications to data transmissions on HF circuits, where practical results are indeed scarce.

In data streams, the errors seem to come in assorted patterns. The independently occurring error model is well known, though seldom observed. The errors may come in bursts, bunches, or at almost regular spacings, to mention a few possibilities. It is not surprising that a given code is more effective for some error patterns than for others. A code to correct t errors in a block may be at loss when faced with (t +1) errors. An ideal burst correcting code, that relies on a presence of a clear guard space, will introduce new errors if confronted with a polluted guard space. Similar comments apply to error detection and combined correction and detection situations.

Knowledge of overall error statistics in time as well as considerable engineering judgement seems to be required for effective code selection. In order to evaluate the performance of a given code, say to within an estimation error of $10^{\pm 2}$ in binary error rate improvement, a final test of real-life measurement is still required. Since measurements and coding hardware are both complicated and expensive, suitable simulation using experimental error time series under the most pertinent conditions may be economically expedient.

5.3. Forward Error Correction

This system relies on an error correcting code, and does not require a backward circuit. It has an advantage of a constant transmission delay which is not dependent on the raw error rate. However, the amount of redundancy required as well as the block length of the code should be determined by the worst error rate conditions to be expected, and therefore, efficiency is appreciably low during the period in which the error rate is not so high. Furthermore, once the correction capability of the particular code is exceeded, the system may introduce additional errors in the decoder output.

As a concrete example, we shall mention the so-called time-spread coding, also known as interleaving, plus an algebraic block coding technique [Fein et al., 1965]. Very recent test results over long-range HF links have been reported by Longchamp [1966]. Table 3 on the next page shows some data for the system having a coding rate of approximately

Table 3. Example of the effectiveness of coding.

(In the table n, k, t, and N denote the code length, number of information bits, number of correctable error bits in a code block, and the number of blocks interleaved, respectively, and e denotes the raw bit error rate in percent. Code 24, 12 was modified 23, 12 Golay code, and other codes were standard BCH codes. Error burst type of distributions were observed in Run Nos. 264, 309, and 339.)

(a) Effect of code length (non-interleaving)

Run No.	e (%)	Percent of errors corrected						
		n = 7	15	24	31	63	127	255
		k = 4	7	12	16	30	64	123
		t = 1	2	3	3	6	10	19
264	0.29	79.1	91.7	95.8	94.2	95.1	94.4	93.1
309	0.43	78.7	94.2	97.4	97.3	97.3	96.6	96.6
339	1.2	62.9	77.7	88.5	84.8	86.6	81.4	81.4
111	0.17	87.8	98.4	98.1	97.3	98.6	100	100
117	0.12	84.3	95.6	96.2	94.5	96.5	98.3	100
121	0.25	86.4	97.6	98.3	98.2	100	100	100

(b) Effect of interleaving in case of Code 24, 12

Run No.	e (%)	Percent of errors corrected			
		N = 5	11	37	61
264	0.29	96.4	97.4	98.6	99
309	0.43	98.9	----	99.65	----
339	1.2	91.9	92.6	94.7	95.2

1/2 (i.e., approximately an equal number of check bits and information bits) under the specified conditions. Extensive interleaving may improve burst situations, while mere longer codes without interleaving perform well in non-burst cases. Note that as interleaving must be done at both terminals, it compounds the elaborate Bose-Chaudhuri-Hocquenghem (BCH) [Peterson, 1961] equipment.

The second somewhat simpler system employs the Gallager type codings [Kohlenberg, 1965]. The remarkable feature of this system lies in its two alternative mode operations corresponding to decoder diagnoses of independent and burst-like error patterns. This is achieved via diffuse threshold decodings [Massey, 1963], and yet is amazingly simple. A version of this system, operating with half-rate code, was tested over certain modems. From the test results, a coding improvement of about two orders of magnitude was estimated when the raw character error rate was 10^{-2}. When the error rate was 10^{-3}, the decoded error was too low to be measured.

Finally, there are a number of studies at other organizations [Lebow et al., 1963; Corr and Frey, 1964; Goldberg, 1965; Mitchell, 1965; Steineck, 1965] on experiments in error control coding. It is probably fair to say that not all of this work was done in the field, but that some laboratory controlled study and simulation were involved.

5.4. Error Detection and Retransmission

This system uses an error detecting code and corrects errors by retransmission of data upon request from the receiver via a backward circuit. The transmission is made block by block with check bits for error detection. This system is more efficient at lower raw error rates, but the efficiency decreases with an increase of raw error rate, until the system is completely blocked at an error rate which is related to the length of the repetition cycle duration. In addition, the transmission delay is variable and dependent on the raw error rate. From the engineering point of view, the system can again be categorized into two classes, i.e., a closed-loop system and an open-loop system.

a. Closed-Loop System

In this system, the transmitter stops transmission each time after transmitting a block of data and waits for the acknowledgment from the receiver. The transmitter sends the next block only after receiving an active (positive) reply from the receiver. When the transmitter receives an inactive (negative) reply or receives no reply from the receiver during an interval of preassigned length, it retransmits the same block. This system has been recommended for the main trunk circuit of the WWW global telecommunication system [Thompson, 1966].

A closed-loop system is applicable to circuits with either simplex or duplex operation. (Simplex operation is defined as an operating method in which transmission is possible alternately in each direction, and duplex operation is defined as the one in which transmission is possible simultaneously in both directions [ITU, 1959].) When only a simplex circuit is available, the use of a closed-loop system is mandatory because, as will be described later, an open-loop system is not applicable to this circuit.

The efficiency in transmission time in a closed-loop system largely depends upon the waiting time during which the transmitter waits for an acknowledgment from the receiver. When the system is operating on a simplex circuit, the minimum waiting time required is the sum of the propagation times in both directions of the radio path and the necessary processing times at both terminals. The minimum waiting time can be the same on a duplex circuit, if data transmission is not taking place simultaneously in both directions. If information data are transmitted simultaneously in both directions on a duplex circuit, the required waiting time depends on the scheme of transmitting the acknowledgment and is longer than the above minimum by at least a block length in any case, unless synchronization of transmitted blocks is maintained in both directions.

b. Open-Loop System

In this system, transmission is made block by block without interruption as long as the transmitter is not requested by the receiver to retransmit the previous blocks. When retransmission is requested by the receiver while the transmitter is transmitting a certain block, the transmitter goes back by a preassigned number of blocks after completion of the block. The number of blocks to be retransmitted depends upon the transmission time required for a block, propagation time, processing time, and other factors. The ARQ system widely used on low-speed radiotelegraph circuits [CCIR Recommendation 342-1] is an example of the system.

An open-loop system is applicable only to a circuit of duplex operation, not to a simplex circuit. When a duplex circuit is available, an open-loop system has higher efficiency in transmission time than a closed-loop system, because no waiting time is required in the former. An open-loop system is applicable to a duplex circuit even when data transmission is made simultaneously in both directions. But the number of retransmitted blocks is generally greater in this case than for the case where data transmission is not made in the reverse direction.

As a variation, the system can be modified so that the receiver advises the transmitter of the block number in which errors have been detected and the transmitter retransmits only the erroneous block after completion of a block being transmitted. By this modification, efficiency in the transmission time is expected to improve, and will not depend upon a reverse channel for data transmission. The only disadvantage of the modified system is that the received data blocks must be sorted in proper order; this may not cause any serious trouble when a telecommunication computer is used at each terminal.

5.5. Combined System

This system is a combination of a forward-correction system and a detection-retransmission system. It uses an error correcting code, and transmission is made block by block, each block being a code word consisting of information bits and check bits. The received block is decoded at the receiver in the same manner as in a forward-correction system. Next, the decoded block is compared with the received block on a bit-by-bit basis, and the receiver requests the transmitter to resend the block as in a detection-retransmission system when the distance between the received and decoded blocks (i.e., the number of different bits) is greater than a preassigned value. Thus, the system can correct a small number of errors by decoding; more errors can be corrected by retransmission.

The underlying idea of this system can be explained by the following simple example. Assume that the minimum distance between each pair of code words is equal to seven, i.e., every code word differs from any other code word by seven bits or more. As a general rule, one can correct up to three errors and detect up to six errors in a block by using this code. Assume also that retransmission is requested when the decoded block differs from the received block by more than one bit. Then, a single error in a block can be corrected properly, and two to five errors can be corrected by retransmission. When more than five errors occur in a block, there are chances of failure in detecting errors because the received block might not differ from another possible code word by more than one bit. The probability that a block is in error after error control in the combined system is equal to the probability that a transmitted code word is converted to a word so that it falls in the neighborhood of radius one of another possible code word. This probability will be compared with those in a forward-correction system and a detection-retransmission system using the same code.

In a forward-correction system using this code, up to three errors in a block in the raw bit stream can be corrected properly; when more than three errors occur in a block, errors will not be corrected, and additional errors will be introduced by decoding. Therefore, the probability that a block is in error after error control in the forward-correction system is equal to the probability that more than three errors occur in a block in the raw bit stream. It is clear that this probability is greater than that in the combined system using the same code.

In a detection-retransmission system using the same code, on the other hand, up to six errors can be detected by retransmission; when more than six errors occur in a block, there are chances of failure in detecting errors. The probability that a block is in error after error control in the detection-retransmission system is equal to the probability that a code word in a block is converted exactly to another possible code word. This probability is smaller than that in the combined system using the same code.

Another important factor in the design of an error control system is efficiency in transmission time. As is evident from the above example, the efficiency is much higher in a combined system than in a detection-retransmission system, especially when burst errors are converted to single errors by utilizing an interleaving technique.

As far as engineering procedures are concerned, a combined system is the same as a detection-retransmission system. Earlier discussion about the latter is applicable to the former. The system can be either a closed-loop, an open-loop, or a modified open-loop system. A closed-loop system can be used on a simplex circuit, while a modified open-loop system will be the best choice for an available duplex circuit.

5.6. Recommended Error Control System

Although it is impossible at the present time to recommend a definite error control system for use in high-speed HF data transmission because of the lack of experimental data, a guideline can be recommended on the basis of the above study.

It is recommended that the error control system be a combination of a forward-correction system for a small number of errors in a block and a detection-retransmission system for a greater number of errors. The system should be of a modified open-loop system, in which the transmitter retransmits only the erroneous blocks upon the request from the receiver. An approximately half-rate code should be adopted.

The use of a closed-loop system recommended in Final Report on WWW Study T.2 [Thompson, 1966] cannot be recommended for HF circuits because, although only a closed-loop system is applicable on a simplex circuit, efficiency in transmission time for this system is much lower than for an open-loop system on a duplex circuit.

6. METEOROLOGICAL BROADCASTS

6.1. General Requirements

As described earlier, the final goal of the design of the WWW global telecommunication system is to construct a system which connects various meteorological centers all over the world by point-to-point metallic circuits. However, this goal is very far from achievement at the present, due to the state of economic development in the world, and HF meteorological broadcasts will have to be used in some parts of the world as substitutes for point-to-point circuits in an interim period. The information to be transmitted by meteorological broadcasts in the framework of the WWW plan includes alphanumeric information and weather maps.

The use of meteorological broadcasts is mainly for economical reasons, and therefore, no sophisticated technique using expensive equipments should be employed for the broadcasts.

As no backward circuit for error control is available for broadcasts, ample margin should be taken into account in the circuit designs.

Techniques used now for HF meteorological broadcasts will be reviewed; technical problems arising from speeding-up of the broadcasts will be also discussed.

6.2. Broadcasts of Alphanumeric Information

In HF meteorological broadcasts of alphanumeric information, binary NCFSK modulation at a modulation rate in the approximate range between 50 and 75 bauds is most widely used. As the preferred values of frequency shift for NCFSK systems operating between about 3 MHz and 30 MHz, CCIR Recommendation 246-1 recommends the values of 200 and 400 Hz.

The data signalling rate in a binary channel operating at a modulation rate of 75 bauds is equal to 75 bits/second and corresponds to approximately 100 words/minute. When a higher data signalling rate is required, speeding-up of modulation rate over 75 bauds is not recommended because of multipath time delay difference. Instead, frequency multiplexing provides a good means to achieve a higher data signalling rate than 75 bits/second. None of the existing CCIR Recommendations is applicable to either frequency shift or subchannel arrangement for frequency-multiplexed HF meteorological broadcast services. As radio receivers having a high tuning stability are not generally used for the purpose of HF meteorological broadcast reception, it is expected that the maximum number of subchannels will be two or three and the minimum frequency shift will be 200 Hz.

When the requirement of speeding-up is only 100 or 150 bits/second, quaternary (4-frequency) NCFSK is an alternate choice. This modulation technique is standardized by CCIR Recommendation 346. The use of this modulation technique makes RF equipments at both terminals much simpler than the use of frequency-multiplexed two-channel FSK does, because a class-C RF amplifier at the transmitter and an amplitude limiter at the receiver are usually already available.

6.3. Broadcasts of Weather Maps

In HF meteorological broadcasts, a weather map is transmitted as a frequency-modulated radio facsimile signal (emission of class F4) modulated by the output of a facsimile scanner. Frequency deviation of ±400 Hz recommended by CCIR Recommendation 343-1 is generally used and the RF signal is transmitted in a 3-kHz bandwidth.

Other factors are standardized by WMO Recommendation 60. Scanning density is approximately equal to 4 and 2 lines/mm for minimum black or white picture elements of 0.4 and 0.7 mm, respectively, and scanning speed of 60 or 120 scans/minute is generally used. It takes about 10 minutes to transmit a weather map of standard size (30 cm x 45 cm) at a speed of 120 scans/minute and scanning density of 4 lines/mm. Modulation rate corresponding to a minimum picture element length of 0.4 mm with a line length of 45 cm at a speed of 120 scans/minute is approximately equal to 1200 bauds. This modulation rate is already too high, if multipath time delay difference is taken into account. The reason that this modulation rate is permitted in practice may be interpreted by the fact that a weather map is redundant from the standpoint of information content. But, in any case, higher modulation rates than this rate cannot be recommended.

Another serious problem arising from speeding-up of the modulation rate in facsimile transmission is a wider bandwidth. On cable circuits a speed of 240 scans/second is available in 3-kHz bandwidth by using a special digital technique for band compression [Veith, 1966] , but the details of this technique are not yet known. It is desirable to study its applicability to HF radio circuits with special emphasis on the effects of multipath phenomena.

7. SUMMARY AND CONCLUSIONS

Technical problems arising from the use of HF radio circuits for the global telecommunication system in the World Weather Watch plan have been studied. Propagation factors affecting HF communications are defined and delineated, modulation-demodulation techniques as well as error control procedures to be used for HF high-speed data transmission are reviewed and consolidated, and technical problems concerning HF meteorological broadcasts are discussed. The main results of this study are summarized as follows:

To achieve high-speed data transmission on point-to-point HF radio circuits, it is recommended that a standard radiotelephone channel of nominal 3-kHz bandwidth be used. It is also highly desirable to lease a commercial radio circuit, wherever possible, unless high-quality HF radiocommunication facilities equivalent to those of commercial radio circuits already exist at both terminals of the particular circuit.

Although there are many possible modems for HF high-speed data transmission, the main difference in the capability among various modems lies in various data signalling rates which can be accommodated in a standard radiotelephone channel by each modem, if each modem is properly designed and operated. When an information transmission rate of 2400 bits/second in a single HF radiotelephone channel is required, the use of an FDPSK modem of Type 2 is probably the only choice. When a lower information transmission rate than the above can be accepted, the use of either a TDPSK modem or an NCFSK modem is also a good choice.

An error control system should be used for HF high-speed data transmission, and the error control system should be a combination of a forward-correction system for a small number of errors in a block and a detection-retransmission system for a greater number of errors. The system should be a modified open-loop system in which the transmitter retransmits only the erroneous blocks upon the request from the receiver. An approximately half-rate code should be adopted.

When speeding-up of HF meteorological broadcasts of alphanumeric information beyond 100 words/minute is necessary, quaternary (4-frequency) NCFSK technique will be most favorable. A frequency-multiplexed binary (2-frequency) NCFSK modem may also be used. A modulation rate higher than 75 bauds should not be used.

No adequate technique exists for speeding-up HF facsimile broadcasts of weather maps. It is desirable to study the applicability of a band-compression technique, developed for metallic circuits, to an HF radio circuit.

8. RECOMMENDATIONS

Based upon the above-mentioned studies on high-speed HF data transmissions and high-rate meteorological broadcasts, the following recommendations can be made on the design of the global telecommunication system in the World Weather Watch Plan:

Recommendation 1

Use of Standard Radiotelephone Channel for High-Speed Data Transmission on HF Radio Circuits

It is recommended

(1) that high-speed data transmission on point-to-point HF radio circuits be achieved via the standard radiotelephone channel of nominal 3-kHz bandwidth, which acually extends from 250 to 3000 Hz; and

(2) that commercial radio circuits be leased, wherever possible, in point-to-point systems, unless high-quality HF radiocommunication facilities equivalent to those of commercial radio circuits already exist at both terminals of the particular circuit.

Recommendation 2

Modems for High-Speed Data Transmission on HF Radio Circuits

It is recommended

(1) that a frequency-differential phase-shift-keying (FDPSK) modem of Type 2 be used for high-speed data transmission on point-to-point HF radio circuit when the information transmission rate is required to be 2400 bits/second in a single 3-kHz channel;

(2) that either a time-differential phase-shift-keying (TDPSK) modem or a non-coherent frequency-shift-keying (NCFSK) modem may be used, when a lower information transmission rate than 2400 bits/second can be accepted; and

(3) that the use of a TDPSK or an NCFSK modem be restricted to such circuits for which the necessity of increasing the information transmission rate is not anticipated in the near future.

Recommendation 3

Error Control Procedures for High-Speed Data Transmission on HF Radio Circuits

It is recommended

(1) that an error control system be used for medium or high-speed data transmission on a point-to-point HF radio circuit;

(2) that the error control system be a combination of a forward-correction system for a small number of errors and a detection-retransmission system for a greater number of errors;

(3) that the error control system be a modified open-loop system in which the transmitter retransmits only the erroneous blocks upon the request from the receiver; and

(4) that an approximately half-rate code be adopted.

Recommendation 4

Speeding-Up of HF Meteorological Broadcasts

It is recommended

(1) that an increase of the modulation rate beyond 75 bauds be avoided for HF meteorological broadcasts of alphanumeric data;

(2) that the choice be made of either a four-frequency NCFSK (diplex or twinplex) modem or a frequency-multiplexed binary NCFSK modem, when the data signalling rate is required to be higher than 75 bits/second for HF meteorological broadcasts of alphanumeric data;

(3) that speeding-up of HF facsimile broadcasts beyond 120 scans/minute be avoided in the modulation techniques presently employed; and

(4) that the applicability to HF radio circuits of the band-compression technique of facsimile signals now under development in the field of land-line facsimile transmission be studied.

9. ACKNOWLEDGMENTS

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11. APPENDICES

11.1. Recommendations Made in the Final Report on WWW Study T.1 [Wüsthoff, 1966]

Recommendation 1

Organizational and Operational Principles of the WWW Telecommunication Network

It is recommended

(1) that the technical characteristics of the telecommunication circuits should be in conformity with the approved recommendations of CCITT, CCIR, and ISO;

(2) that the highest degree of compatibility of telecommunication equipment used in the WWW-circuitry should be reached; and

(3) that uniform technical procedures for the operation of the network should be obtained.

Recommendation 2

Rate and Type of Modulation in WWW Telecommunication Circuits for High-Speed Data Transmission

It is recommended

(1) that special-quality telephone-type circuits (bandwidth 3100 Hz) should be leased, wherever possible, in the point-to-point system;

(2) that the data signalling rate should be:

(a) 2400 bits/second in the final high-speed system (main trunk and connections to the Regional Meteorological Centers and Regional Telecommunication Hubs);

(b) 1200 bits/second in those segments of the system in which the rate of 2400 bits/second cannot be implemented at the beginning, for an interim period (first phase), and 2400 bits/second in the second (final) phase; and

(3) that the preferred type of modulation should be the phase modulation.

Recommendation 3

Telecommunication Code for High-Speed Data Transmission in Circuits of WWW

It is recommended

that a special telecommunication code for meteorological circuits should be used, as outlined in Study T.2, provided that all computer-equipped Meteorological Centers adopt such a code.

Recommendation 4

Error Protection in the WWW-Telecommunication Network

It is recommended

that the principles for error protection, laid down in Study T.2, should be implemented.

Recommendation 5

Standardization of HF Radiotransmission on Medium and High-Speed in the WWW Telecommunication Systems

It is recommended

that the technical standards for medium and high-speed data transmission on meteorological point-to-point links and for meteorological radio-broadcasts should be studied in order to permit the standardization of these transmissions in the WWW telecommunication system.

11.2. Recommendations Made in the Final Report on WWW Study T.2 [Thompson, 1966]

Recommendation 1

Telecommunication Procedure

It is recommended

(1) that the processed data be transmitted as far as possible in a numeric form to save transmission time and facilitate the use of the data by computers;

(2) that the telecommunication procedures be the same for observational as for processed data when exchanged between computers; and

(3) that the CCITT/ISO plus a special numerical code be used together with a condensed "envelope" (heading and end of grouping) to keep the number of bits to a minimum.

Recommendation 2

Pre-Processing of Observational Data

It is recommended

(1) that error control be made, both with regard to observational and procedural errors at the earliest possible stage;

(2) that, if the station location is not originally coded as geographical co-ordinates, this conversion be made before dissemination to the NMC's; and

(3) that the decoding of the messages be done before dissemination, if the NMC's so wish.

Recommendation 3

Transmission Codes

It is recommended

(1) that the CCITT/ISO code be used as the basic telecommunication code for exchange of data between computers;

(2) that the proposed numerical code be used within the CCITT/ISO code for exchange of numerical information; and

(3) that the Telegraph Alphabet No. 2 be used on telegraph circuits as long as the present types of teleprinters are still in use. When new equipment is installed it should preferably work with the CCITT/ISO code or the Telegraph Alphabet No. 2.

Recommendation 4

Error Control

It is recommended

(1) that a quality check be made as early as possible in the collecting system so that the data is as error free as possible when reaching the error protected circuits;

(2) that an error detection and correction (EDC) system be used on medium or high-speed circuits, especially between computers; and

(3) that the EDC system be a closed loop system using decision feed-back with retransmission. The transmissions be block by block of variable length with cyclic check bits. The number of check bits being 12 or 16 depending on the undetected error rate decided upon.

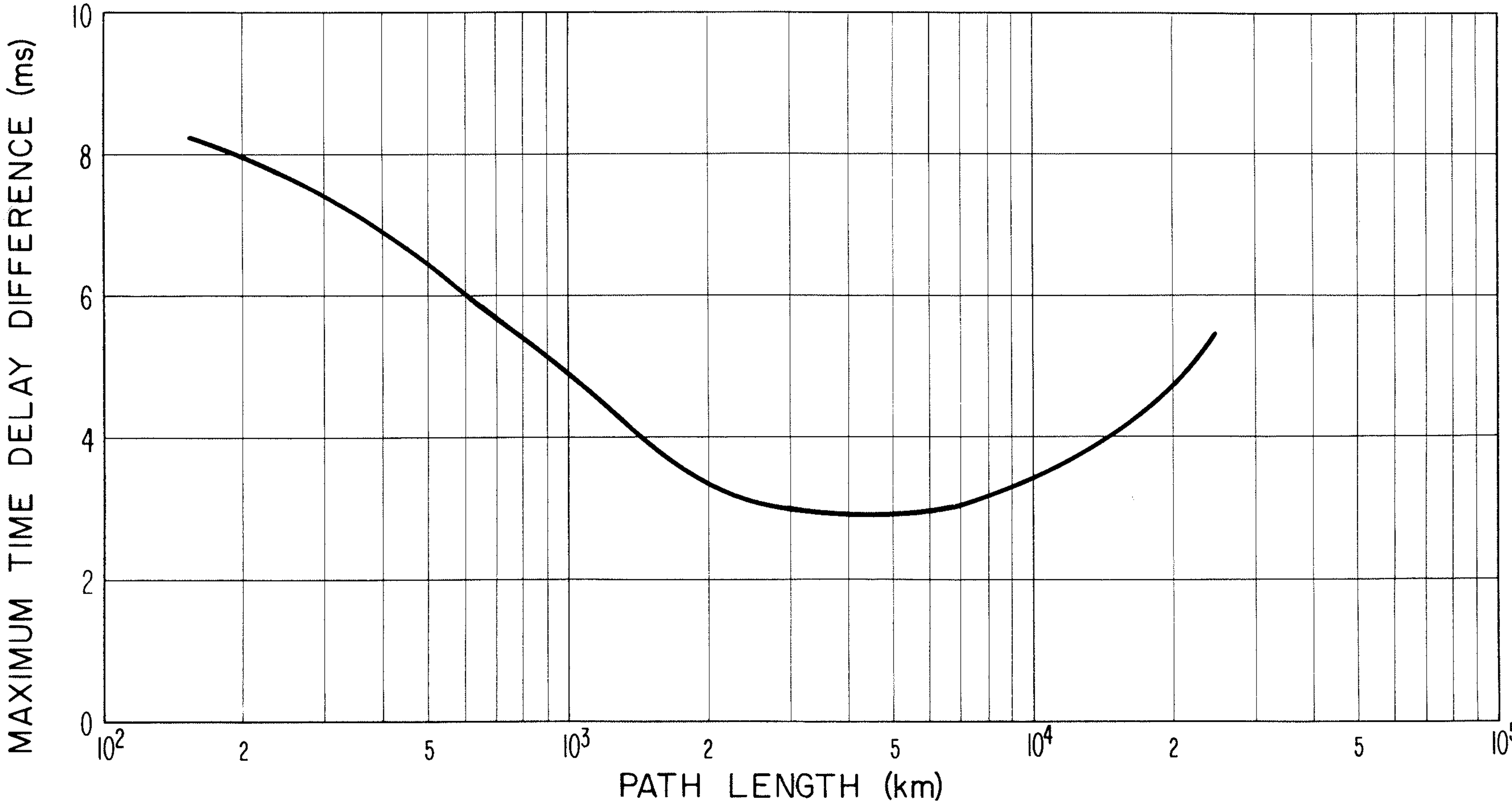

Figure 1. Maximum expected multipath time delay difference.

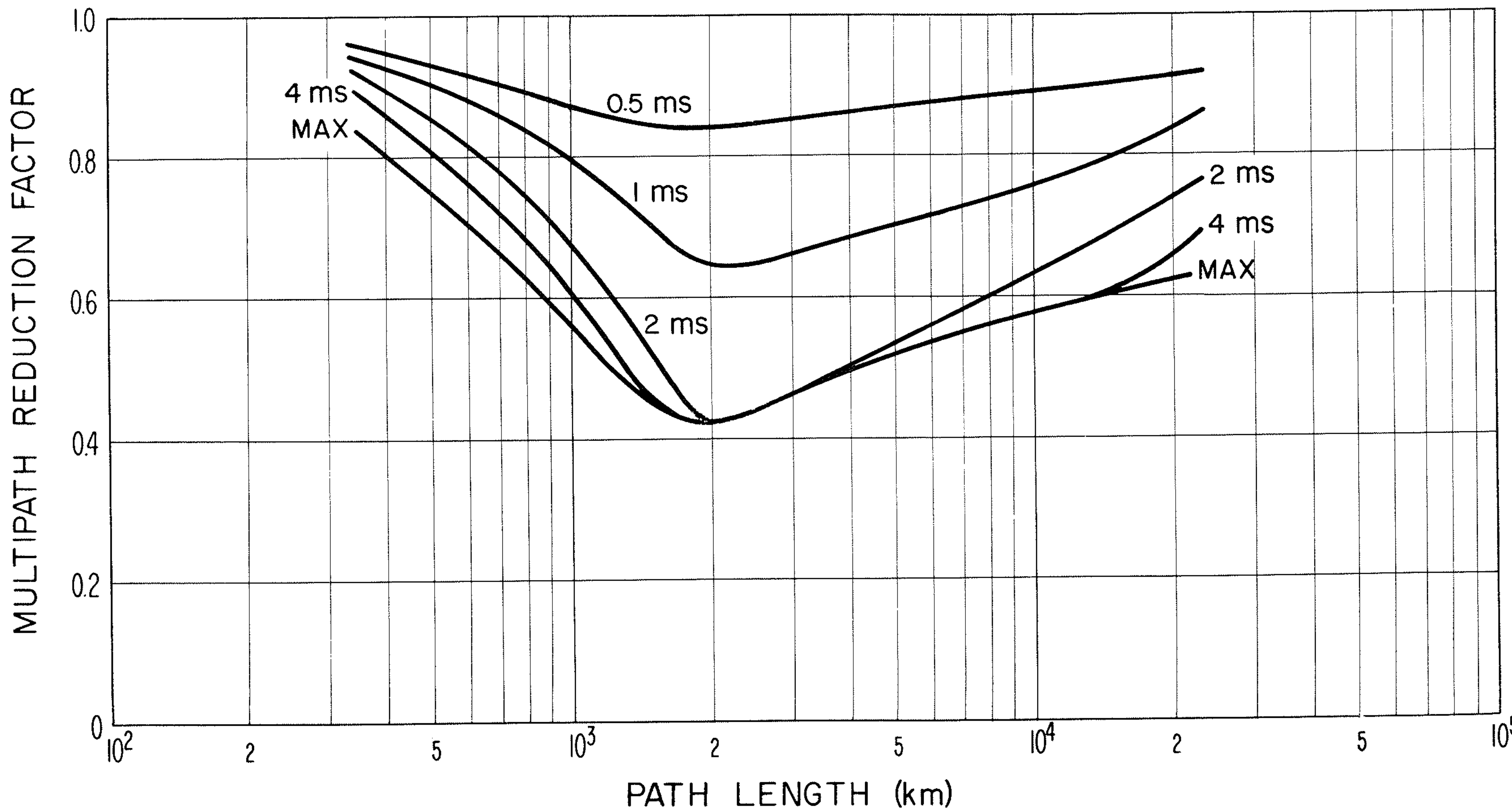

Figure 2. Multipath Reduction Factor (MRF) for various multipath time delay differences.

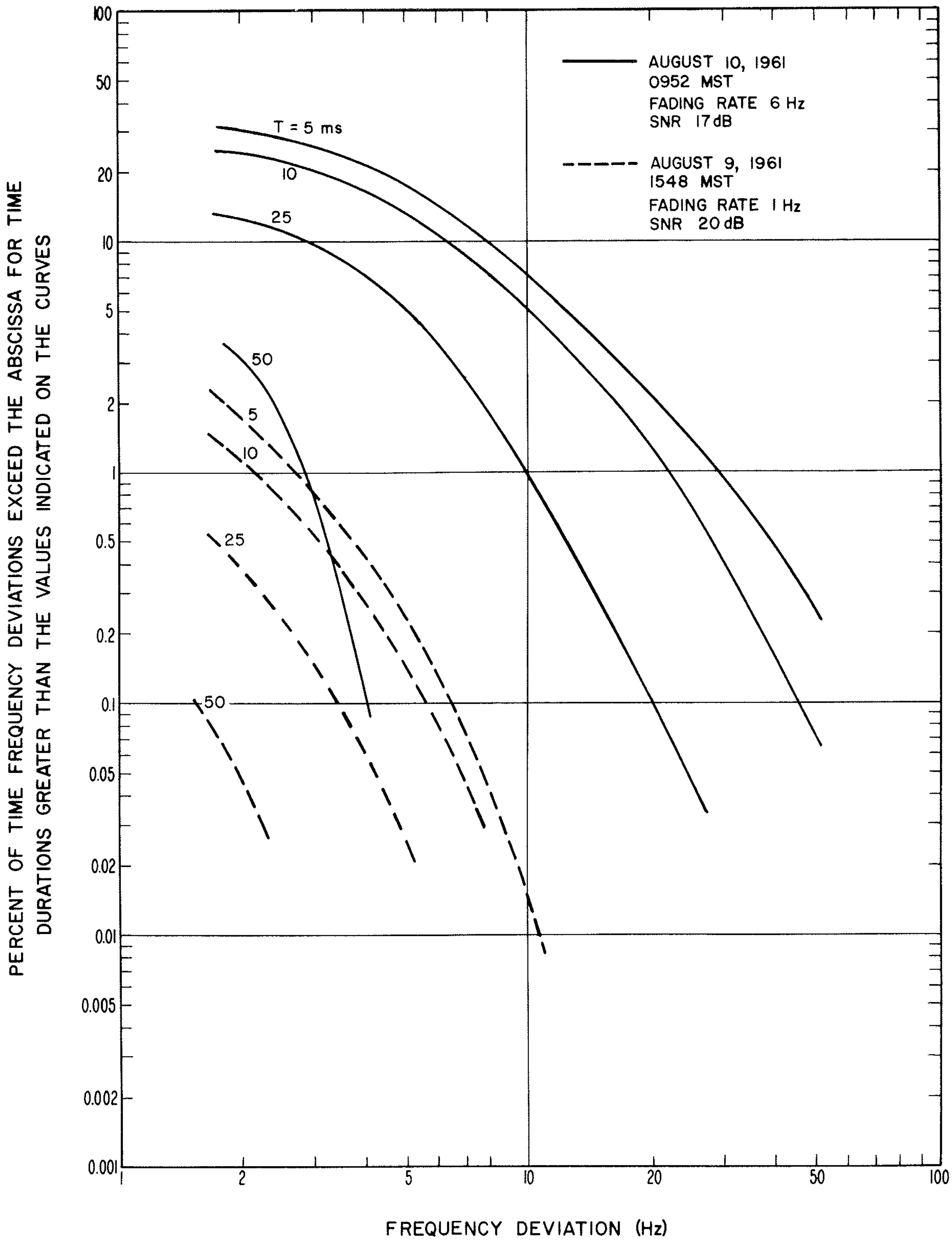

Figure 3. Distribution of frequency fluctuations for various time durations observed at 14.688 MHz on a 4500-km auroral path from Barrow, Alaska, to Boulder, Colorado.

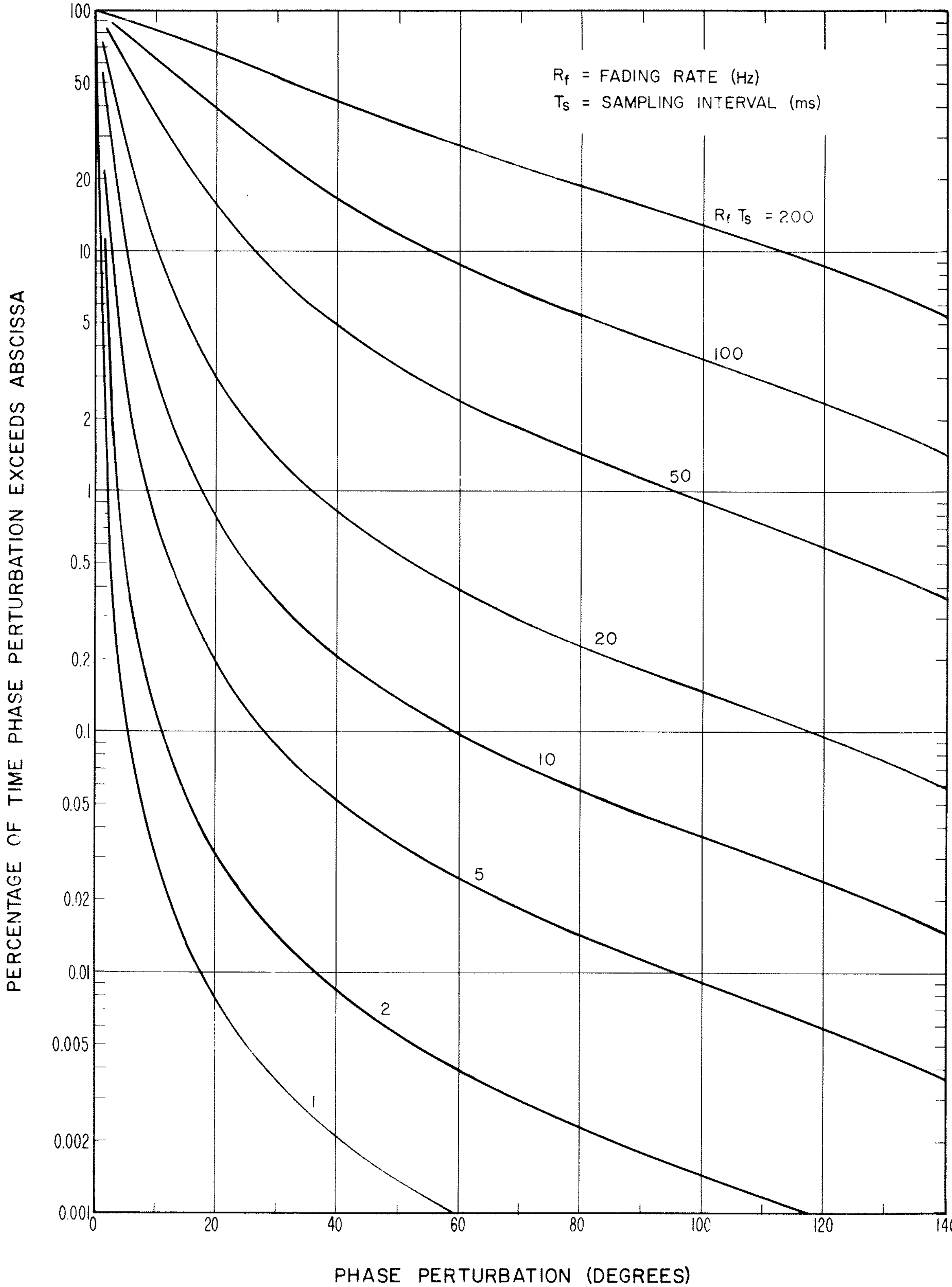

Figure 4. Theoretical distributions of phase fluctuations for Rayleigh fading signals at various sampling intervals.

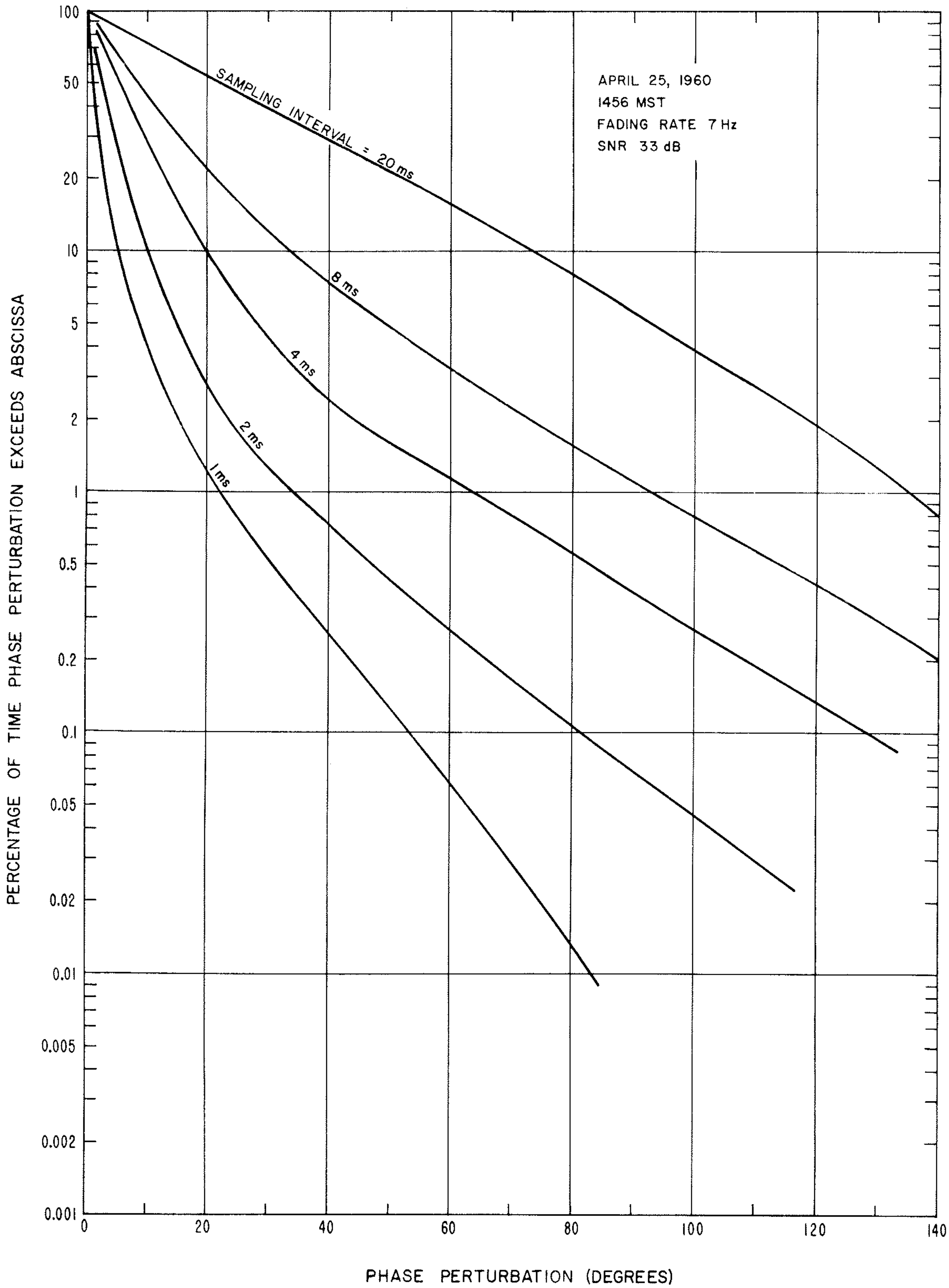

Figure 5. Sample distributions of phase perturbations for various length sampling intervals observed at 19.247 MHz on a 4500-km auroral path from Barrow, Alaska, to Boulder, Colorado.

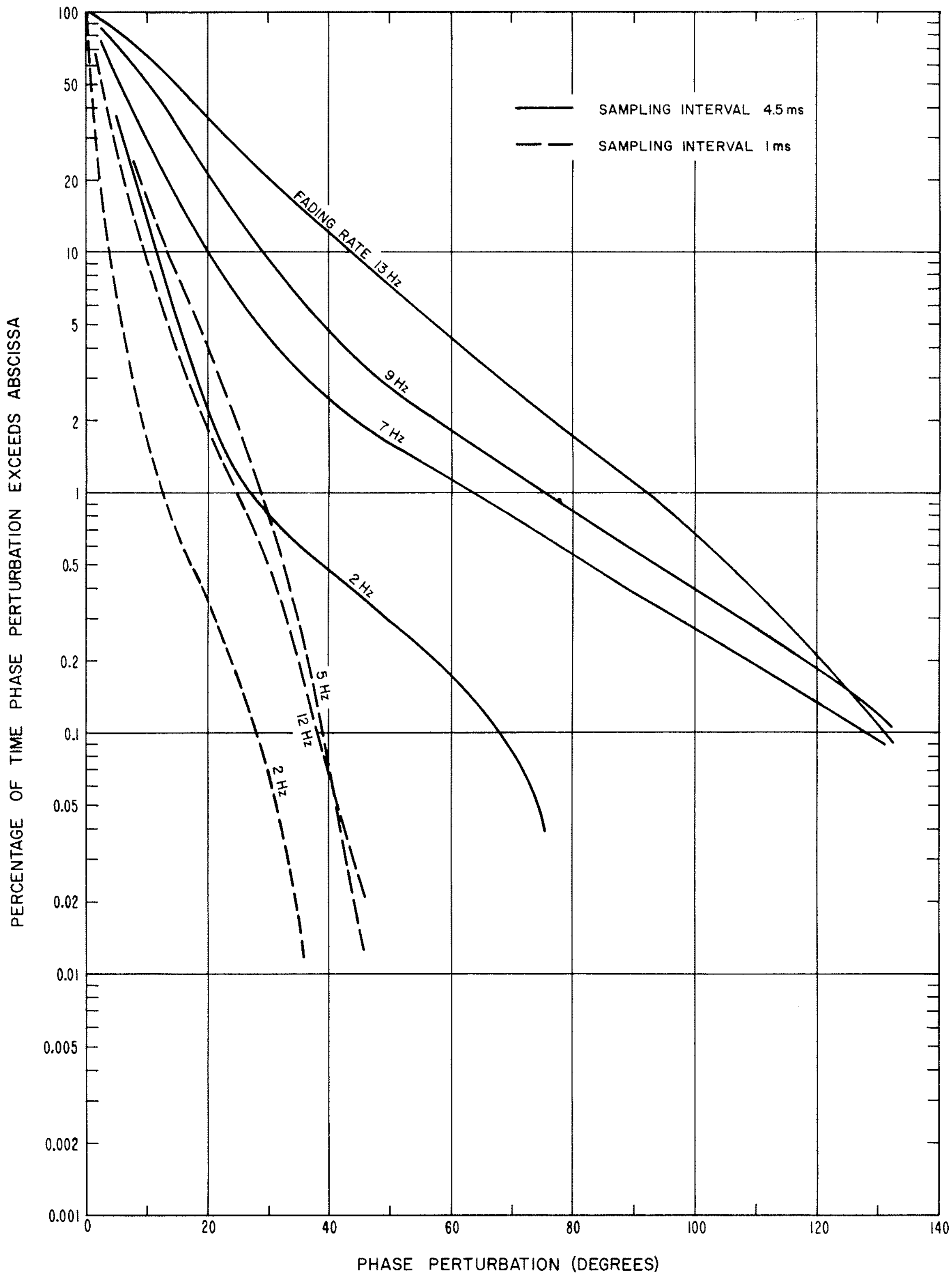

Figure 6. Distributions of phase perturbations for different fading rates observed at 14.688 and 19.247 MHz for sampling intervals of 1 and 4.5 milliseconds, respectively, on a 4500-km auroral path from Barrow, Alaska, to Boulder, Colorado.

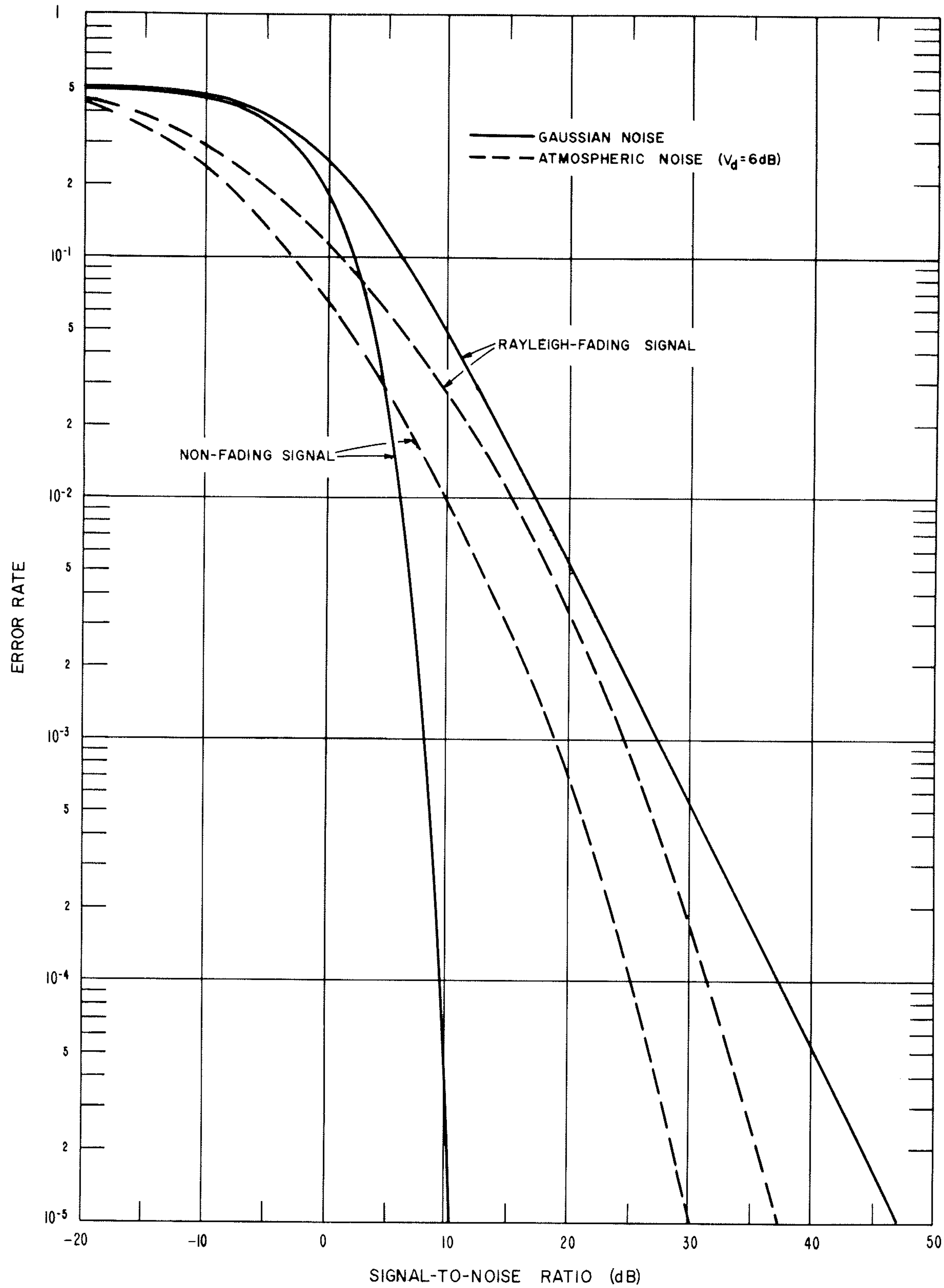

Figure 7. Theoretical error rates in a binary NCFSK system.

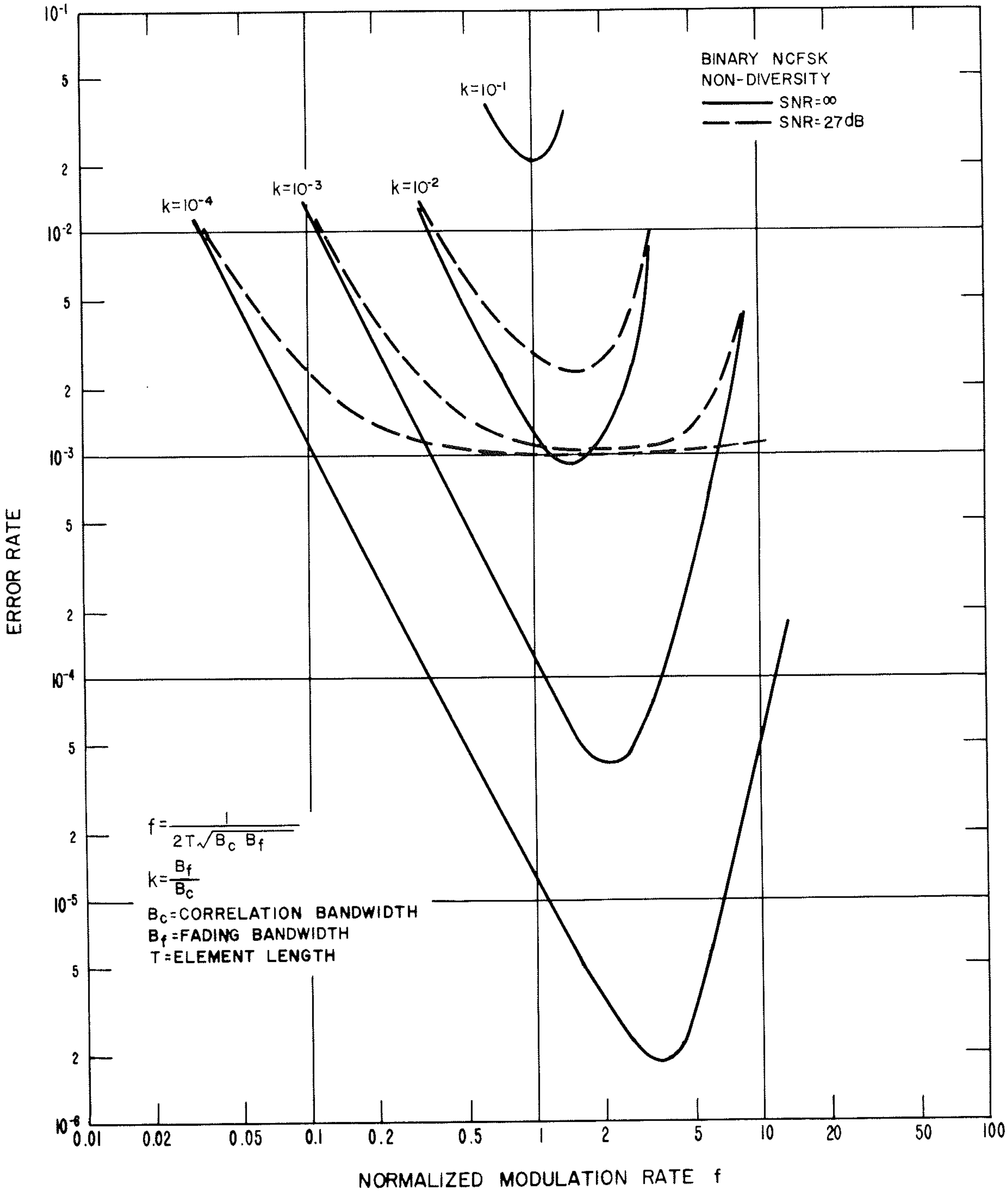

Figure 8. Error rate in a binary NCFSK system with no diversity as a function of the normalized modulation rate (normalized with correlation bandwidth and fading bandwidth).

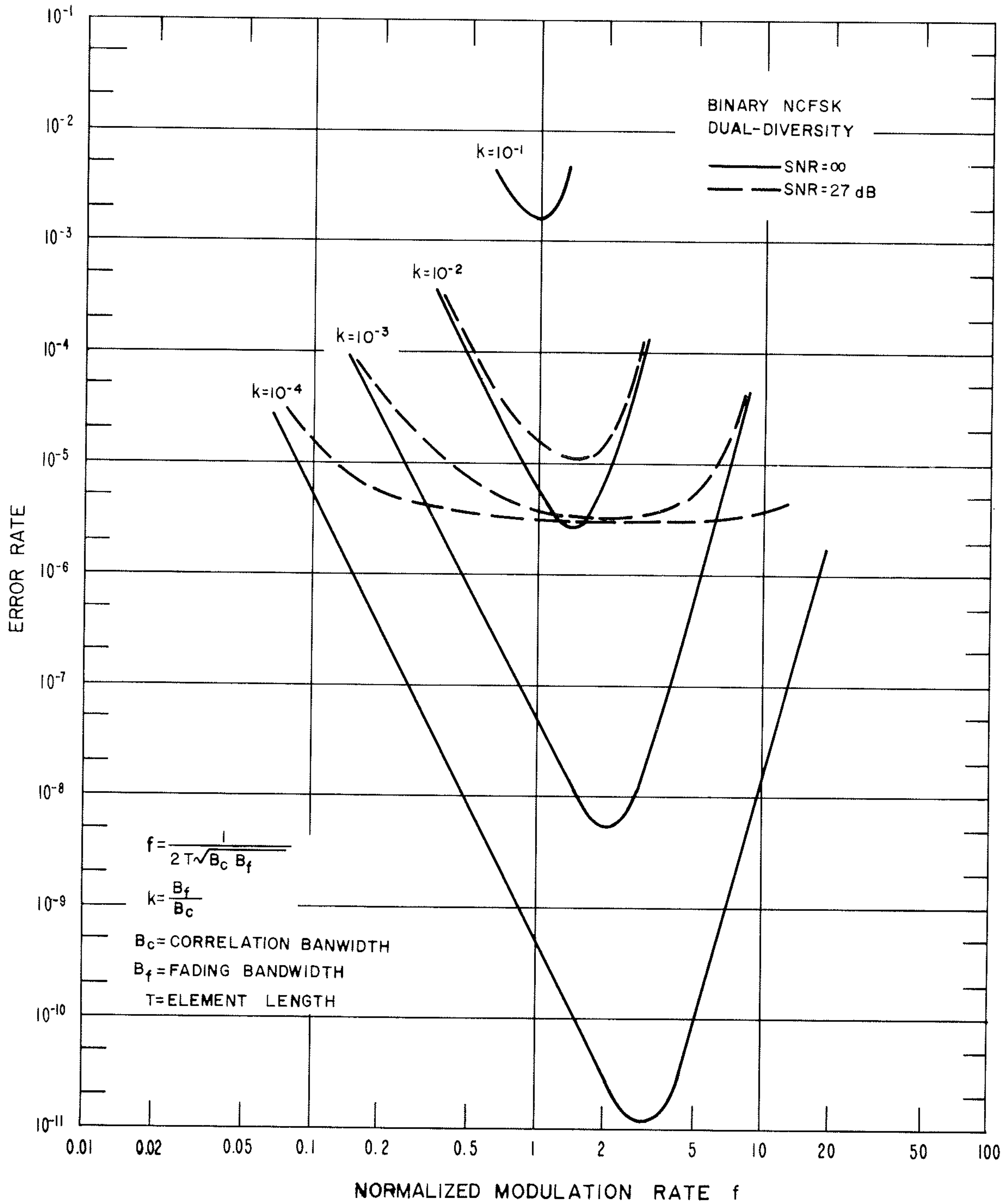

Figure 9. Error rate in a binary NCFSK system with dual diversity as a function of the normalized modulation rate (normalized with correlation bandwidth and fading bandwidth).

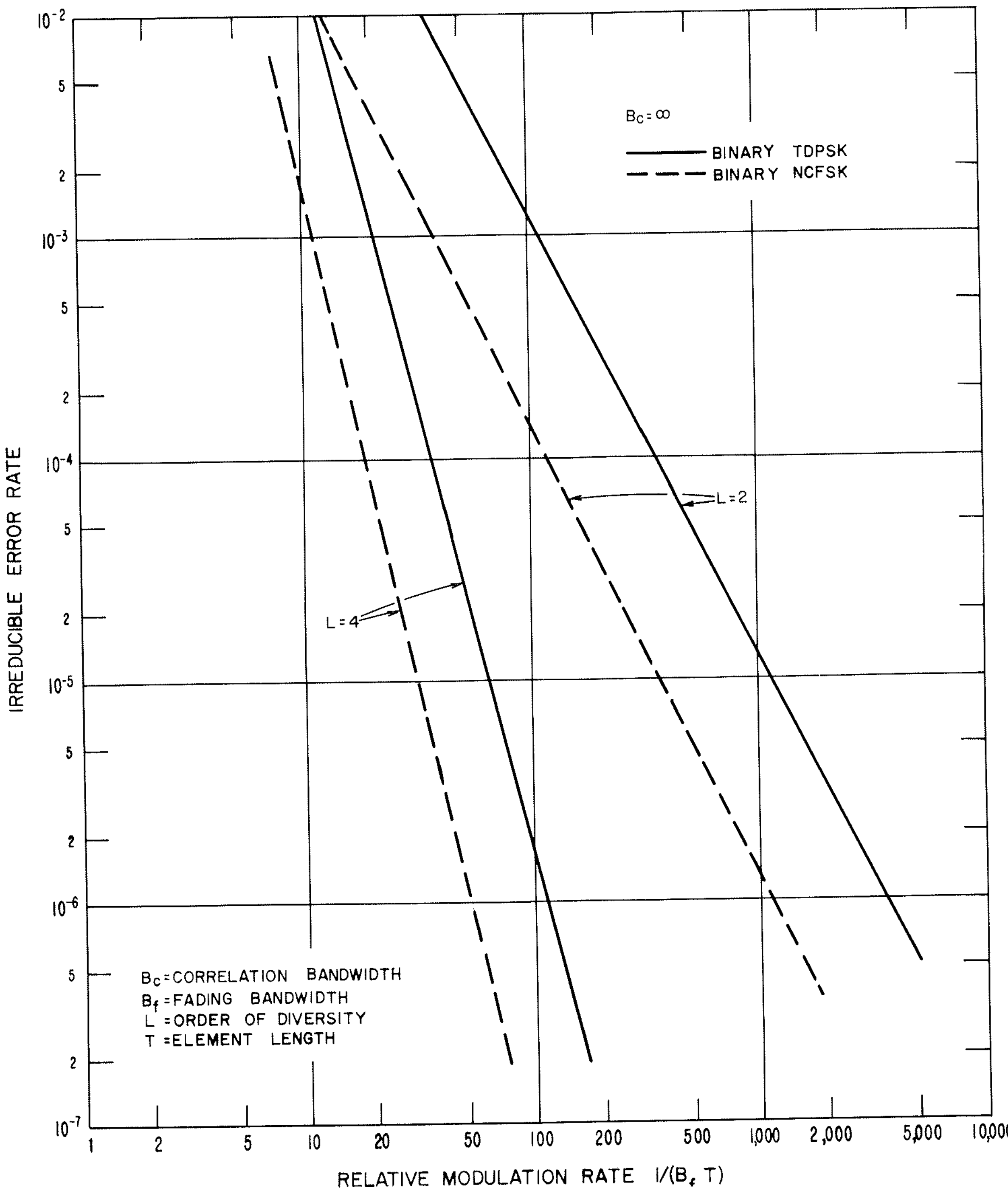

Figure 10. Rate of irreducible error in a binary TDPSK and NCFSK systems contributed by the effect of time-selective fading. (An exponential fading autocorrelation function is assumed.)

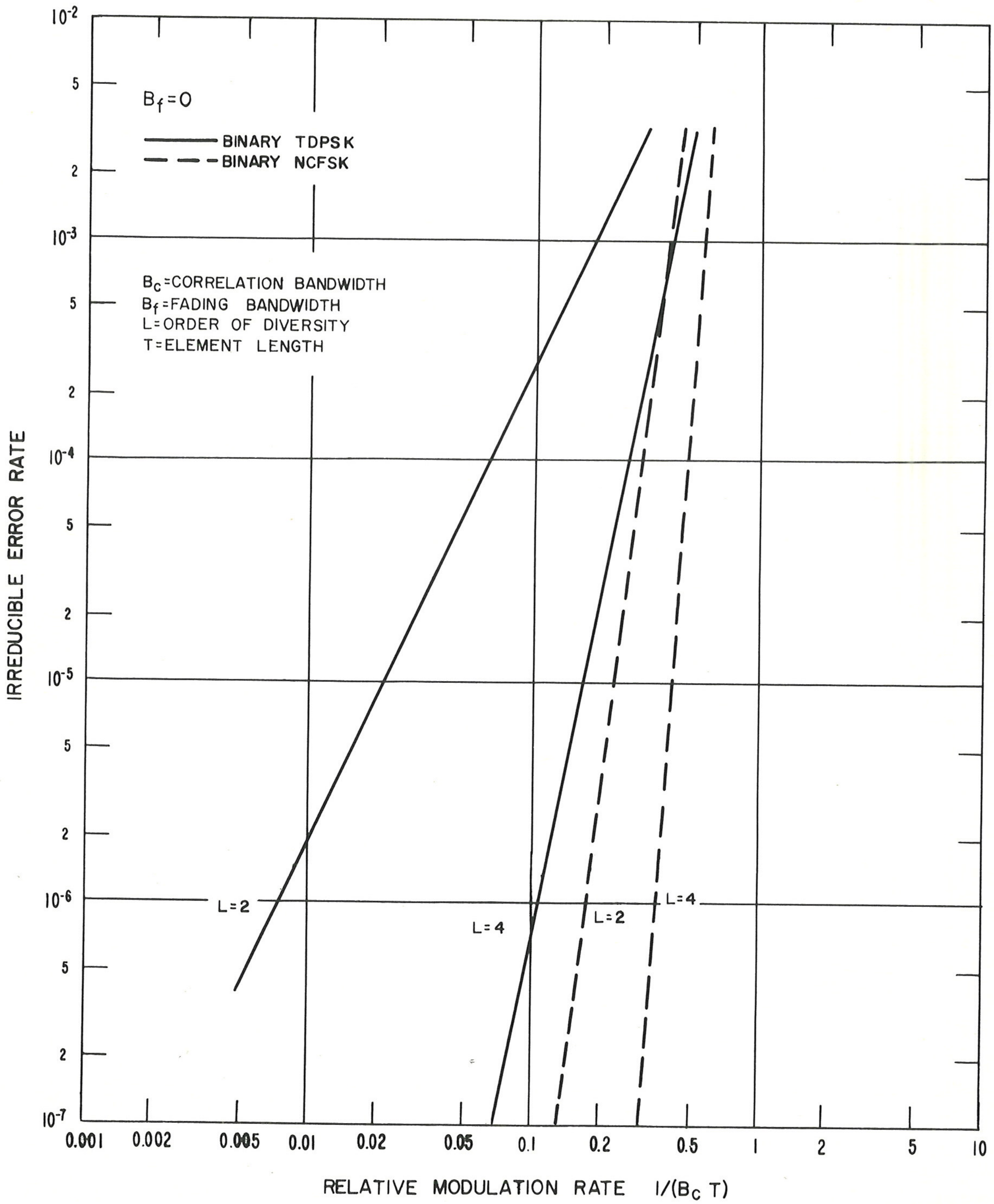

Figure 11. Rate of irreducible error in a binary TDPSK and NCFSK systems contributed by the effect of frequency-selective fading.

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