INVESTIGATION OF DIGITAL MOBILE RADIO COMMUNICATIONS

111423

INVESTIGATION OF DIGITAL MOBILE RADIO COMMUNICATIONS

By

THOMAS C. KELLY
JOHN E. WARD

This project was supported by Grant Number NI-71-129-G awarded by the National Institute of Law Enforcement and Criminal Justice, Law Enforcement Assistance Administration, U.S. Department of Justice, under the Omnibus Crime Control and Safe Streets Act of 1968, as amended. Points of view or opinions stated in this document are those of the authors and do not necessarily represent the official position or policies of the U.S. Department of Justice.,

October 1973

U.S. DEPARTMENT OF JUSTICE
Law Enforcement Assistance Administration
National Institute of Law Enforcement and Criminal Justice

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C., 20402 - Price $1.60
Stock Number 2700–00233

Abstract

There has been considerable activity over the past few years in the development and testing of vehicle printers and two-way data terminals for use in law enforcement communications. Although the mobile voice-radio channel has an audio bandwidth similar to that of the voice telephone network, for which reliable data transmission rates up to 10,000 words per minute are now routine, it has proved to be a much poorer channel for digital transmission, and many tests have experienced high error probabilities even at data rates corresponding to only 100-300 words per minute--substantially voice rate.

This report presents the results of a one-year technical study of digital data transmission over land-mobile radio channels. Much of the report is devoted to description and analysis of the two major problems of the radio channel--multi-path fading and ambient impulsive noise--and their relative effects on error rates for various types of data modulation. It is concluded that multi-path fading is the dominant limitation, and that both space and frequency diversity transmission should be investigated as means of combating its effects and improving the reliability of high-speed data transmission. A data rate of 2,000-2,400 words per minute is suggested as a reasonable goal for law enforcement digital communications, both to speed up call-response cycles and increase channel capacity as compared to voice transmission.

Other topics discussed are coding for error detection and correction, operational and spectrum utilization issues, the role of portables in a digital world, and economic factors. Several appendices contain information and viewpoints gained in discussions with equipment manufacturers and police departments, and a glossary of terms.

CONTENTS

CONTENTS (Contd.)

CONTENTS (Contd.)

FIGURES

FIGURES (contd.)

TABLES

CHAPTER 1

INTRODUCTION

The rapid progress over the past ten years in computerized data bases and in direct, on-line man-computer "conversations" to access these data bases has opened new horizons in law enforcement. The value of being able to quickly check if an auto registration is "hot", if a suspect is on a wanted list, or if an item is on a list of stolen articles, and so forth, is attested to by the growing use of the interconnected local, regional and national law enforcement information systems.

To date, this rapid direct access to data bases has developed around "land-line" technology and thus has been restricted to fixed terminals with wired connections to the computer(s). Despite the greatly improved inquiry response time that has been attained by placing computer terminals at the radio dispatcher's elbow, a mobile unit must still state its inquiry to the dispatcher by voice radio, and receive his response by the same means. There obviously could be further reduction in response time, plus considerable reduction in air time and dispatcher load, if mobile units were able to communicate directly with the data base by high-speed digital radio transmission, bypassing the voice conversation with the dispatcher. Some trials of this concept are already underway.

Digital radio communication is also attractive for other reasons. Perhaps the most widely publicized experiments over the past few years have been with mobile printers that provide a hard copy printout of dispatcher-generated messages to the mobile unit, be they base-station initiated dispatches or responses to mobile inquiries. Some departments have felt that the hard copy printout of all messages represents an important gain, even if the dispatcher must key in all messages. Advantages cited are the hard-copy record itself, the security aspect (the greatly increased difficulty of channel monitoring and the fact that at the vehicle messages cannot be heard by suspects within earshot of the radio or external speaker), and the unattended receipt of messages. However, there are some problems when printers are used for all communications. The main problem is that the patrolman in a one-man car cannot safely read a received message while he is driving. Others have cited the fact that in digital systems, each printer message is usually addressed only to the one vehicle for which it is intended, whereas voice communication can be heard by all units on the channel. While some feel that this improves operations by eliminating "message sorting" by the mobile units, others feel that this "private" communication between a dispatcher and each of his units loses something in general awareness of all units on duty as to what is going on. Thus it might be said that printers represent an important new technology whose proper role in law enforcement communications remains to be worked out in the future.

Another potential advantage of digital transmission is its great speed compared to voice transmission, which can permit much more information to flow over the same channel bandwidth, greatly reducing spectrum congestion For example, a data rate of 2400 bits per second, which seems feasible over a voice-bandwidth channel, represents a 16-fold improvement over voice rate (150 words per minute), which corresponds to 150 bits per second when transmitted in coded-character form. The reason that the word potential is emphasized above is that present printers operate at 100-150 words per minute, substantially no different than voice rate. Although the use of digital message addressing and acknowledgement procedures in printer systems has significantly reduced channel overhead (compared to voice procedures), the messages themselves are still going at voice rate, and only part of the potential of digital communication for relief of channel and spectrum congestion has yet been realized.

This brings us to the main topic of this report--the technology of digital communication over mobile radio channels. The particular problem which underlies all else is the question of digital errors, brought on by the fact that radio fading and noise conditions that are perhaps merely irritating in voice transmission can cause data errors in digital transmission. The reason for this is that noise spikes can look just like data bits to the receiving equipment (or mask them), and signal losses of only a small fraction of a second (due to fading) that are unnoticeable in voice reception can cause missing data bits. These sources of error cannot be completely eliminated, and actually, an occasional error is not disastrous since messages can be checked for errors and retransmissions requested as necessary. The real questions are: what is an acceptable error rate, under what conditions can it be obtained, and what are the possibilities for improved digital transmission over what is possible today?

Chapter 2 of this research report analyzes the mobile radio communication medium to determine the effects of mobile radio signal propagation and random noise on digital communication. The approach is technical and mathematical; but the results are stated in general form in the chapter summary. Chapter 3 discusses the other side of the communication coin--the economic, and operational aspects of such a new digital mobile communication system. Chapter 4 builds upon the understanding gained in Chapters 2 and 3 to present specific methods for achieving rapid, reliable digital mobile radio communication. Particular topics discussed are the problem of link discipline in many-to-one digital systems operating on a common channel, the possibilities for use of diversity reception techniques to reduce or eliminate channel fading and thereby improve the channel for digital transmission, and the tradeoffs between simple error-detection coding and more complex error-correction coding for improvement of channel efficiency in terms of net throughput of correct messages.

Appendix A discusses one additional technical topic--the minimum digital data rate and maximum error rate for acceptable transmission of voice in digitized form. The required rate turns out to be 30,000 bits per second, considerably greater than the data rates of 100-2500 bits per second discussed for digital radio channels.

During the course of the project, a number of visits were made to mobile radio equipment manufacturers to discuss their present activities and future plans in digital transmission. Also, visits were made to several police departments to discuss their present operations, future plans, and the role that they foresaw for digital communications. These various visits are reported in Appendices B, C, and D. A brief glossary of terms used in the report is given in Appendix E.

The general summary and conclusions from the study are given in Chapter 5.

CHAPTER 2

THE MOBILE RADIO CHANNEL

The mobile radio communication medium is the VHF/UHF electromagnetic spectrum, with present bands from 25-50 MHz (VHF low-band), 144-174 MHz (VHF high-band), and 450-470 MHz (UHF band). In 1971, the FCC added a fourth band from 806-947 MHz (re-allocated from UHF-TV and Government services), but actual use of this new band is still at least a year or more off because of the time required to develop and produce new equipment, and the continuing study by the FCC (Docket 18262) as to how this new 900-MHz band will be used. The FCC also in 1971 granted permission for mobile users in the top 10 urban areas to share the bottom 7 UHF-TV channels (470 to 512 MHz) on a not-to-interfere basis. These frequencies are contiguous to the present UHF band and may be lumped with it for purposes of this discussion.

Each of the four mobile bands represents a unique combination of propagation and noise problems--for instance, the lower bands are more subject to impulsive noise interference from vehicle ignition systems and other man-made sources while the higher bands have more difficulty with multipath propagation effects and thermal (Gaussian) noise. All bands experience shadow falling, but the effects differ with frequency.

In this chapter we consider the properties of the mobile radio channel as it effects digital signals transmitted over it. The two primary effects are amplitude variations caused by propagation anomalies, and additive noise. Both of these dynamically effect the signal-to-noise ratio (SNR) at the receiver and thus the quality of transmission, which for digital transmission may be characterized by the probability of errors.

In Section A we discuss both shadow and multipath fading in mobile radio signal propagation, carefully distinguishing between the two. Multipath propagation is analyzed in some detail from two points of view--time domain (pulse "echoes") and frequency domain (superposing sinusoids)--and it is shown that the Rayleigh probability density is a suitable model for multipath amplitude fading. However, frequency selective fading and direct transmitter radiation are noted as exceptions to the general Rayleigh distribution. Finally, the Doppler frequency shift is examined, and it is shown that for land-mobile vehicle speeds the shift is so small that it may usually be neglected.

Section B discusses noise. The well-known Gaussian model for random noise is discussed briefly, but most of the section is devoted to impulsive noise; both the measurements that have been reported and the models that have been developed to describe it. The results of Sections A and B are used in Section C to calculate error probabilities for combined fading and noise. Section D summarizes some general observations about fading and noise effects on digital transmission.

A. Propagation Effects

In this section, the emphasis is on base-to-mobile propagation. Note however that by the general reciprocity theorem* as applied to mobile radio communication, the transmission characteristics from base-to-mobile are the same as the characteristics from mobile-to-base, i.e., the same propagation mechanisms (shadowing, multipath, Doppler shift) work both ways.

---

*Ramo, Whinnery, Van Duzer: Fields and Waves in Communication Electronics, (Wiley, New York, 1967) page 587.

1. Shadow fading

The major identifying characteristic of "shadow fading" is a more-or-less uniform reduction in signal over an area whose dimensions are many tens of wavelengths. Wavelength of course depends on signal frequency, and in the mobile bands,varies from 1.05 feet at 950 MHz to 37.6 feet at 25 MHz. The shielding or attenuation which causes shadow fading may be due, for instance, to large buildings in urban areas or geographical features in rural areas.

A second characteristic of shadow fading is that all signals within a given mobile band are usually "shadowed" together. This is because the shielding effects of metal-frame buildings or the attenuation of obstructing geographical features change so slowly with frequency that signals over the relatively narrow range of any one mobile radio band are all similarly reduced by shadowing. From one band to another, though, the shadowing effect may differ significantly. For example, metal-frame structures can only shadow signals whose wavelengths are larger than or comparable to the spacing of the structural members, and a building with large glass windows of, say, six-foot dimensions may effectively shield out low-band signals (wavelength = 35 feet) but pass 950-MHz signals (wavelength = 1 foot). In general, high frequency (short wavelength) signals provide better penetration and more complete coverage in the presence of structural shadowing.

The variation in shadowing effectiveness of gentle geographical features can also vary from band to band. High-frequency signals tend to follow line-of-sight paths and pass over the shadowed area, while low frequency signals "fill in" and provide better area coverage around gentle geographical variations.

A third characteristic of shadow fading is that it is non-statistical in nature (as opposed to multipath fading, which is probabilistic in nature). From the physical processes which cause shadow fading, it is quite clear that shadowed areas are permanently determined by local geography and structures and that those shadowed (i.e., "low-signal") areas can be uniquely located and identified. It is then clear that statistical measures are unnecessary for the description of shadow fading situations, or in the design of mobile systems which will operate in the presence of shadow fading.

2. Multipath propagation

Multipath propagation exists whenever radio signals arrive at a receiver via multiple, presumably distinguishable, paths. In the multipath geometry of Fig. 1, for instance, the received signal is a superposition of three versions of the transmitted signal, one "direct" signal

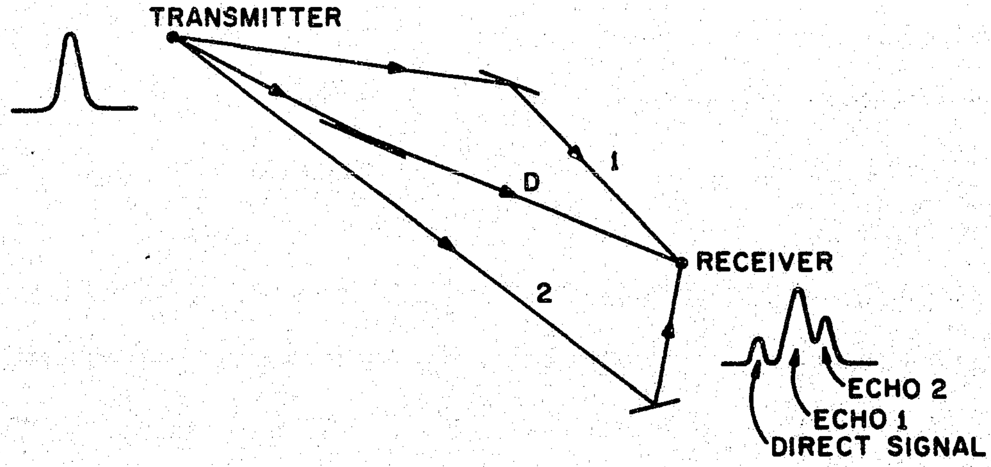


Fig. 1 Simple multipath propagation geometry showing a direct signal and two echoes.

and two reflected, delayed signals. The relative attenuations of these three versions depend on the particular circumstances. If the transmitted signal were a short pulse the receiver output would contain a "direct" pulse signal plus two multipath "echoes" as shown.

The simple geometry of Fig. 1 may not seem very realistic, but actual pulse measurements that have been reported for such complicated propagation environments as Manhattan,[1] the Chicago loop,[2] and the San Francisco financial district[3] show the same type of delayed, attenuated echoes as may be predicted from our simplified multipath model (see Fig. 2). In practice the path delays and path attenuations vary randomly with mobile position and thus have to be described by their joint probability densities. Note also that relative time delays of more than ten microseconds beyond the direct signal are very rare so that the maximum multipath time delay may be safely taken as 10 microseconds, corresponding to a maximum path-length difference of 3 km.

The frequency domain description of multipath propagation is based on the probabilistic superposition of several independent sinusoidal carriers of the same frequency, but with random amplitudes (individual path attenuations) and random phase (path delays). Lord Rayleigh[4] in 1880 analyzed the limiting case of an infinite number of randomly phased, equal-amplitude (infinitesimal) sinusoidal signals. Although the Rayleigh probability density is very convenient for calculations, the assumption of an infinite number of signal components might seem to rule it out for mobile radio propagation. However, it turns out to be a good model, as will be described.

In 1946, Slack[5] analyzed the more realistic (and more difficult) cases of up to seven equal-amplitude, randomly phased sinusoids and her resulting amplitude densities for N=2 through N=7 are replotted in Fig. 3.

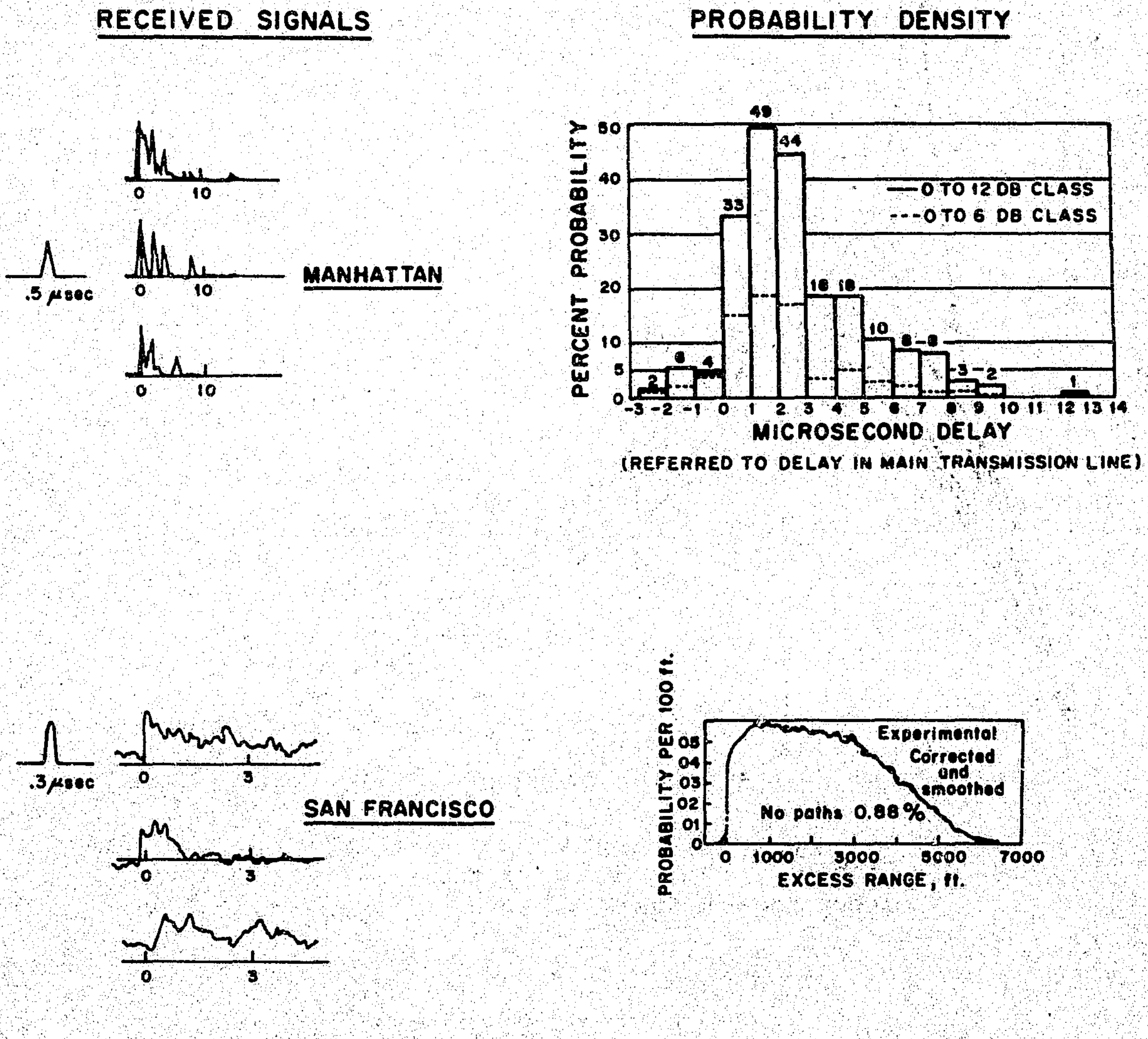


Fig 2 Experimental measurements of multipath echoes[1,3]

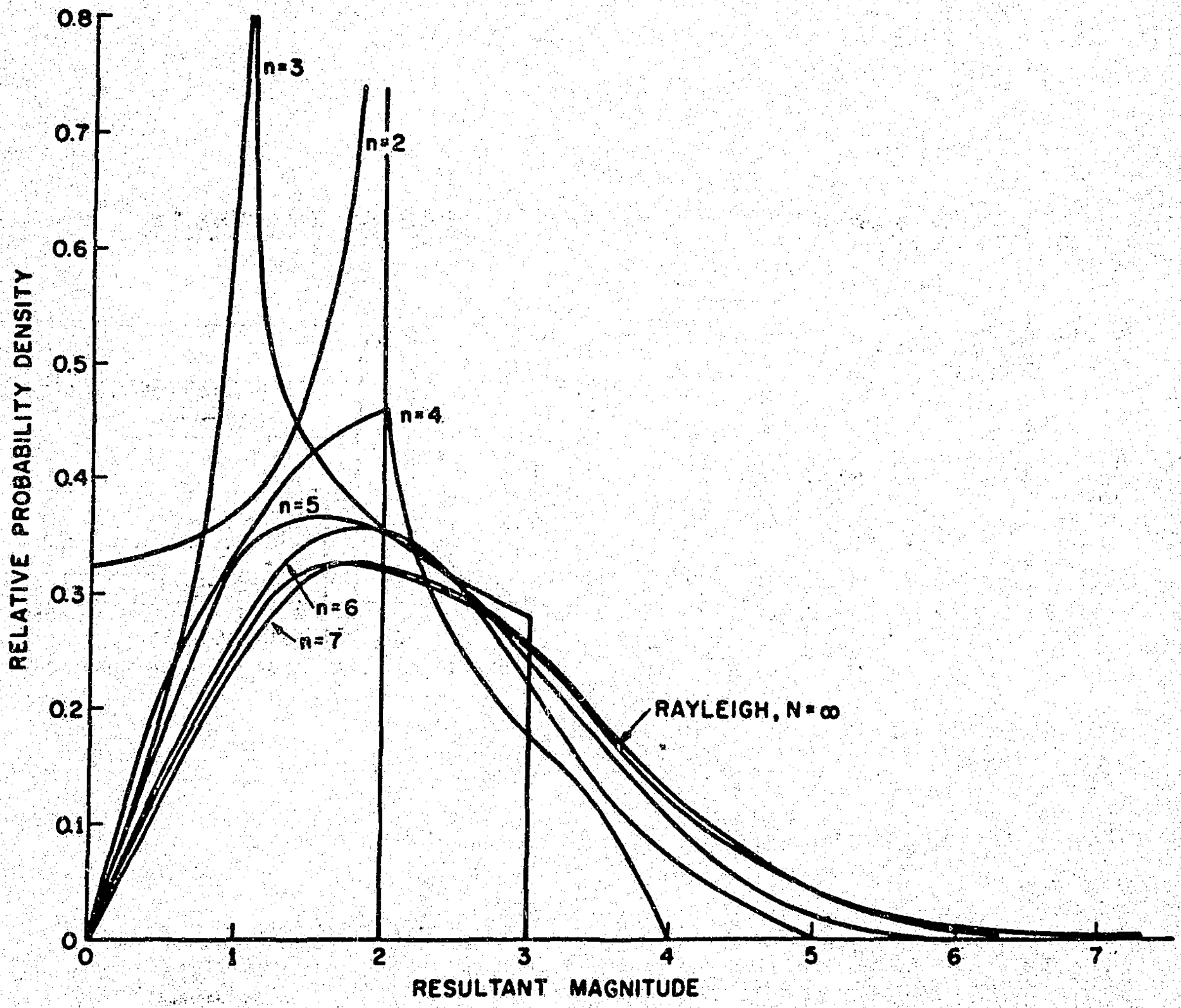


Fig. 3 Probability densities for the resultant amplitude of N independent, randomly phased unit sinusoids (N=1 to 7).[5]

The corresponding Rayleigh density, whose mean has been adjusted to equal the N=7 case, is also plotted and it is seen that the N=7 curve is a close approximation to the Rayleigh density for all values of the resultant, and that even the N=3 curve varies linearly with the resultant (just like a Rayleigh density) for small values of the resultant. From this we conclude that even for a small number (N=3 to 7) of combining equal-amplitude sinusoids, the ensemble of resultant amplitudes is closely approximated by the Rayleigh distribution.

The "equal-amplitude" assumption also does not seem to be an issue in the use of the Rayleigh model. A number of recent authors[7,8,9] have experimentally measured carrier amplitude variations in the mobile bands over a wide range of mean carrier amplitudes and found that these experimental means can be closely modeled by the Rayleigh distribution. Thus the frequent references to the ideal (and mathematically tractable) Rayleigh statistic for carrier amplitude fading seem justified, even though the assumptions of equal component amplitudes and an infinite number of independent components which lead to the Rayleigh statistic obviously are not often satisfied.

One failure of the Rayleigh amplitude statistic is its inability to account for frequency distortion in multipath propagation. Schwartz[10] has shown that signals whose bandwidth, B (Hertz), satisfy the relation

$$BT \geq 10$$

where T is the maximum differential multipath time delay (seconds), have the property that the amplitude statistics of widely separated frequencies within B are independent. This condition is called "frequency selective fading". As previously stated, the pulse measurements in typical urban environments indicate a "worst case" time delay of 10 microseconds for urban multipath propagation. If it is desired to insure independent fading of two signals (for example, for frequency diversity reception), the necessary frequency separation may then be calculated as:

$$\Delta f \gtrsim 10 \frac{1}{T} = \frac{10}{10\ \mu\text{sec}} = 1\text{ MHz} \quad \text{(for independent fading)}$$

Schwartz's results also show that if, instead,

$$BT \leq 0.1$$

then the statistics of the frequency components of the signal are closely correlated and the amplitude of the otherwise undistorted signal will be Rayleigh-distributed. This is called "flat" or "non-selective" fading. Using this relation and the 10-μsec delay figure, the bandwidth over which there should be no frequency-dependent multipath effects is about equal to the normal channel bandwidth:

$$B \lesssim 0.1 \frac{1}{T} = \frac{0.1}{10\ \mu\text{sec}} = 10\text{ kHz} \quad \text{(non-selective fading)}$$

Besides the fact that it does not account for frequency selective distortion, the Rayleigh model apparently is not always accurate at very low amplitudes relative to the median. This is illustrated by experimental measurements that have been reported, which are plotted in Fig. 4. The 11.2-GHz measurements are seen to fall right on the Rayleigh curve, whereas the 836-MHz and 150-MHz points are respectively higher and lower. One reason for the measured deviations from Rayleigh at 150 MHz might be that the measurements included some shadow fading effects, which would tend to decrease the signal amplitudes. The 836-MHz measurements, on the other hand, might have included a weak direct signal component, distorting the measurement upward. This second possibility (direct component plus a Rayleigh-distributed component of random phase) has been examined analytically by

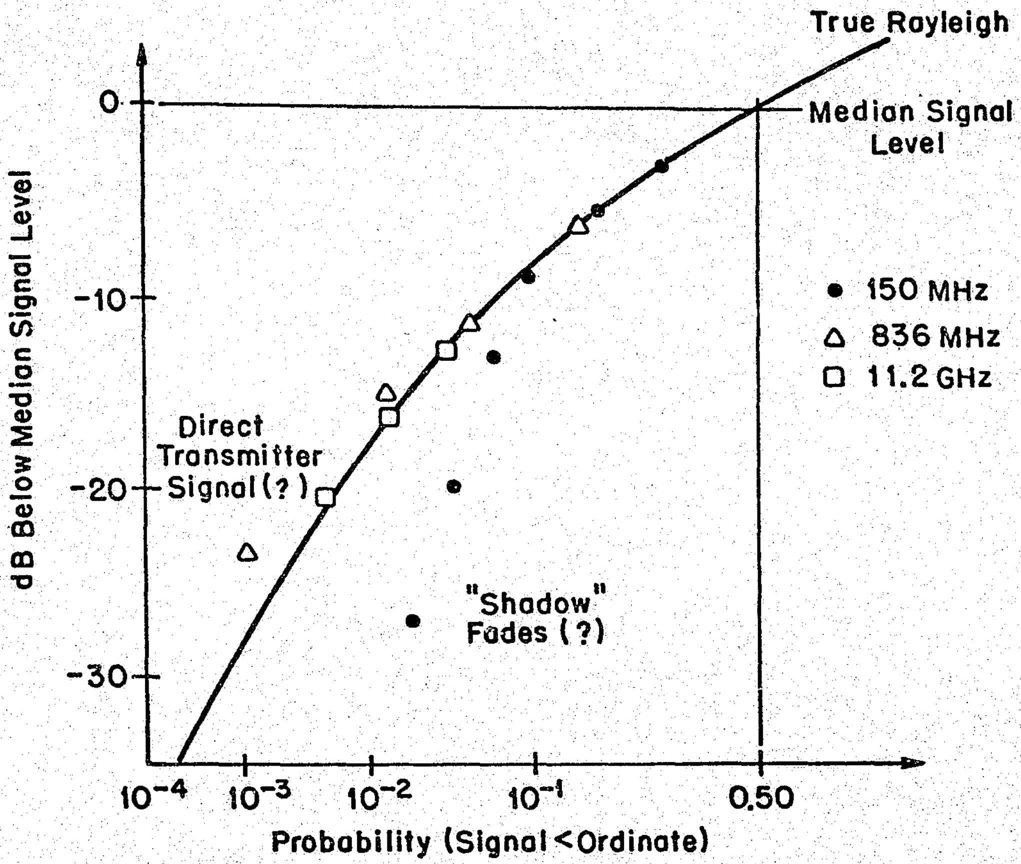


Fig. 4 Deviations from the Rayleigh amplitude statistics for signal amplitudes much below the median.[7,8,9]

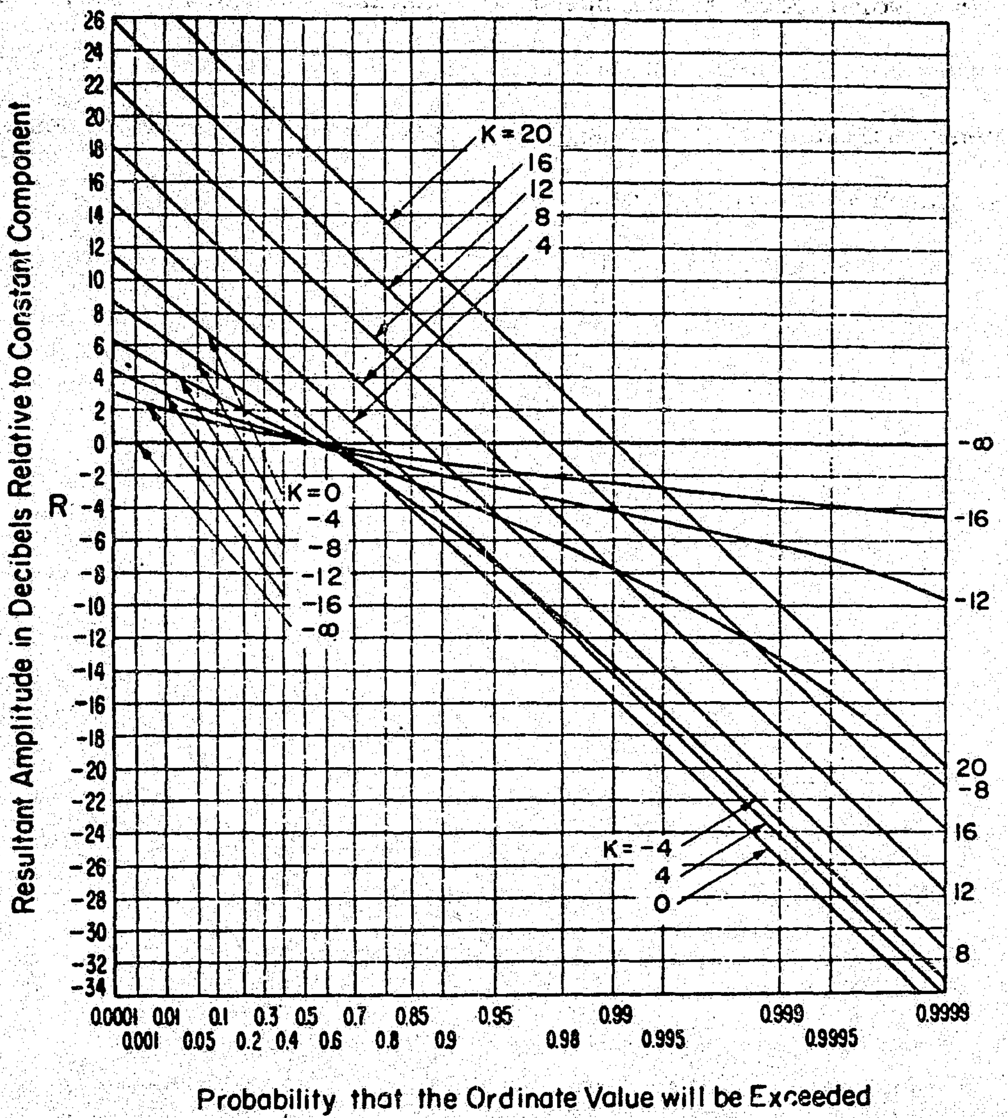
Norton et al,[11] whose resulting probability distributions are shown in Fig. 5. In Fig. 5, the parameter K is the ratio of the power in the random component relative to that in the constant component, in dB. The analysis shows that the Rayleigh distribution in unaffected so long as the average power in the random (Rayleigh) components is greater than the total power in the direct component, but that the distribution rapidly becomes non-Rayleigh for K less than 0 dB (equal power).

To sum up this section on multipath propagation, multipath propagation can manifest itself as delayed, attenuated echoes (time domain) or amplitude fading (frequency domain). In can also be concluded that for mobile radio carrier fading due to multipath propagation, the Rayleigh distribution is a simple and accurate statistical model for amplitudes within approximately 20 dB of the signal mean. In contrast with shadow fading, multipath fading is a random phenomenon which is not limited to specific locations. Multipath fading is also short-term: the signal level may not remain faded over distances much greater than a half-wavelength (rather than tens of wavelengths as in shadow fading) and, as we have seen for frequency-selective distortion, the statistical variations of multipath amplitudes within a narrow frequency band may be as different as shadow fading's effect from one band to another.

3. Doppler shift

Radio signals to and from mobiles are affected, as one would expect, by the fact that the mobiles may be in motion, causing a Doppler frequency shift or random frequency modulation. The shift may be upward or downward in frequency, depending on the direction of motion, and in magnitude is equal to

$$|\Delta f| = f_o V/c$$



Note: From Reference 11. Power in the random component is K dB relative to the constant vector.

Fig. 5 Probability distribution for a constant vector plus a randomly-phased Rayleigh-fading component.

where f_o is the unshifted frequency (Hertz), v is the relative radial speed between transmitter and receiver (meters per second), and c is the radio propagation velocity in air (3×10^8 meters per second). Assuming 100 miles per hour as a worst-case radial speed for the land-mobile service, the corresponding Doppler shift at 450 MHz is only 67 Hz, considerably less than the frequency tolerances for state-of-the-art (1972) mobile radio oscillators which are standardly 0.0005 percent or, at additional expense, 0.0002 percent. The latter of these corresponds to a possible maximum frequency variation at 450 MHz of:

$$|\Delta f| \leq (450 \text{ MHz})\ (0.0002\%) \quad = \quad 900 \text{ hertz.}$$

An interesting property of Doppler shift is that it is independent of signal power. Due to its small absolute effect, however, it will be ignored hereafter.

B. Channel Noise

1. Gaussian noise

A number of authors have made detailed analyses of Gaussian noise and its effect on digital transmission for several forms of digital modulation. The analysis of Gaussian rather than some other distribution of noise is justified both by the Central Limit Theorem, which asserts that the sum of a large number of noise samples tends toward a Gaussian noise distribution, and by information theoretic channel capacity arguments which state that Gaussian noise is a "worst possible" noise in the sense that the Gaussian channel capacity is less than the channel capacity for any other noise distribution of equal noise power. Additive Gaussian noise has the further advantages for analysis purposes that (1) signals and additive noise may be separately analyzed (superposition) in linear systems, and

(2) Gaussian noise remains Gaussianly distributed after passing through a linear system.

A typical result for three types of digital modulation, frequency-shift keying (FSK), phase-shift keying (PSK), and differential phase-shift keying (DPSK), is shown in Fig. 6 (from Schwartz, Bennett, and Stein, 1966, page 299)[10]. These error probabilities are appealing in their simplicity and they have been used to rank digital modulations according to error probability, but several cautions should be borne in mind:

(1) The error curves of Fig. 6 are only valid for Gaussian noise; other types of noise such as co-channel interference, telephone switching noise, or vehicle ignition noise, which have decidedly non-Gaussian distributions may have quite different error characteristics.

(2) In Fig. 6, the signal-to-noise power ratio is assumed to be constant. For cases in which the signal is randomly fading, an integration over the power probability density is necessary to arrive at the new average error probability (see below).

(3) The overall system is assumed to be linear. Nonlinear systems, especially bandwidth exchange systems, will distort the error distribution.

The special case of Rayleigh-fading signals in Gaussian noise (item 2 above) has been examined by Stein (ref. 10, p. 408) and his results are shown in Fig. 7. Comparison with Fig. 6 shows that the error probabilities are greatly increased over the non-fading case for a given signal-to-noise ratio. The relative ranking of the three types of digital modulation remains the same, however.

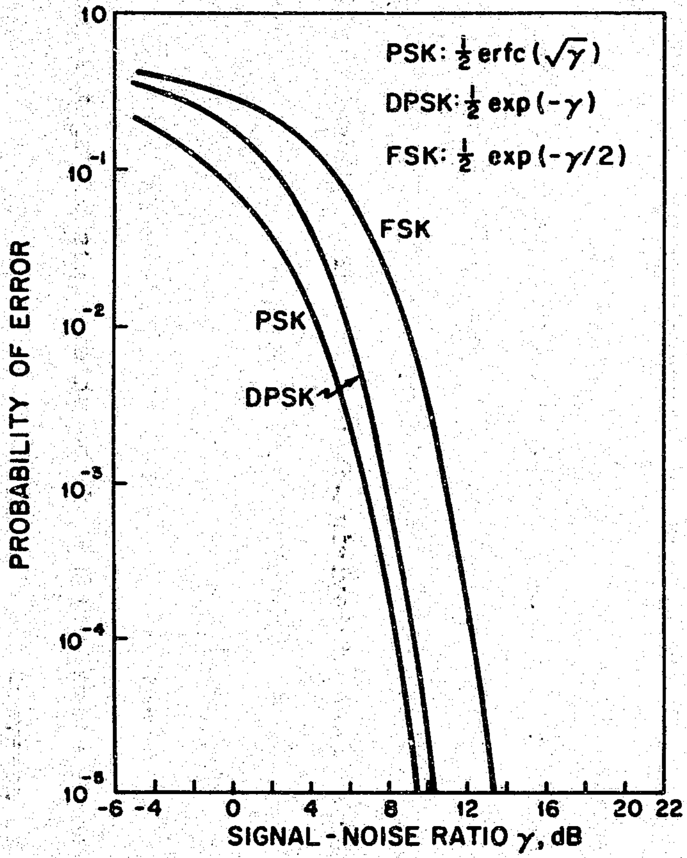


Fig. 6 Probability of binary error in Gaussian noise.[10]

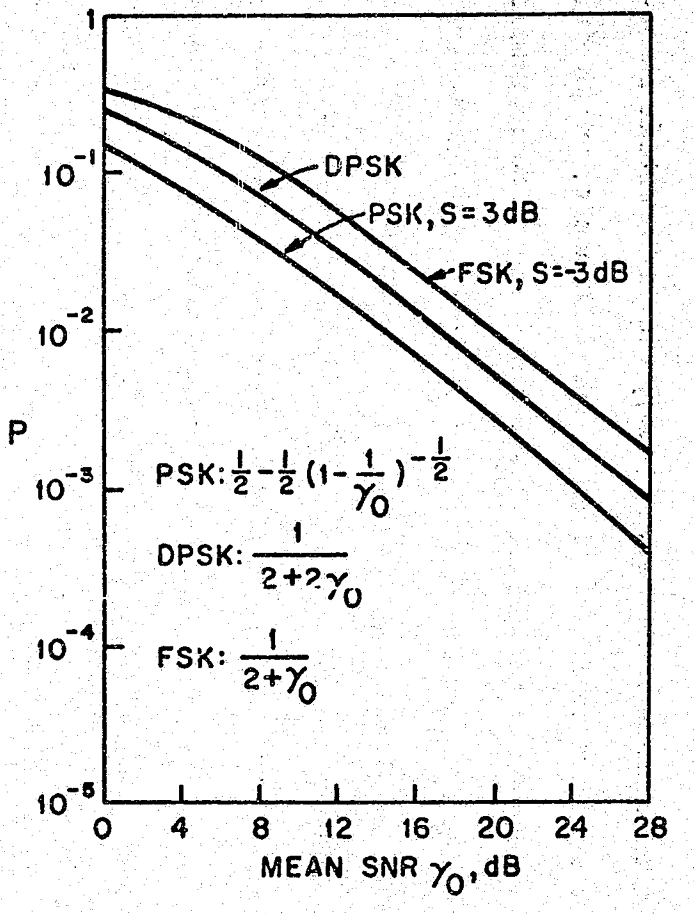


Fig. 7 Probability of binary error for Rayleigh-fading signals in Gaussian noise.[10]

2. Impulsive noise

Despite the tractability and general validity of the Gaussian model for certain kinds of noise, as discussed above, the class of noise called "impulsive" is so different from Gaussian noise that the Gaussian probability distribution model cannot be used to predict its effect on communication performance (in our case, digital error probability). Impulsive noise includes such man-made noises as power-line corona, vehicle ignition radiation, arc welders, and power switching, and naturally occurring atmospheric noise. The reason for the inaccuracy of the Gaussian model when impulsive noise is present is almost common sense: only rarely does a zero-mean Gaussian random variable have a very large amplitude relative to the square root of its variance, but an impulsive noise is expected to have large amplitudes. For equal noise powers (i.e., for the same mean square amplitudes), Gaussian and impulsive noise random variables have very different probability densities, as shown in Fig. 8. Impulsive noise is especially important to digital communication because the probability of digital error for signals in impulsive noise is larger than the probability of error in Gaussian noise of equal noise power. In order to show this analytically, however, it is first necessary to discuss experimental measurements of impulsive noise and the models that have been developed to describe it.

a. Urban noise measurements

Impulsive noise appears to be the predominant noise in urban and suburban areas. As shown in Fig. 9, man-made noises mask the weaker Gaussian thermal noise at frequencies below 500 MHz (suburban) or 2 GHz (urban)*. It is also interesting to note that naturally occurring atmospheric radio noise

---

*A private communication from Motorola indicates that the man-made background noise in New York City is as high as 50 uvolts per meter.

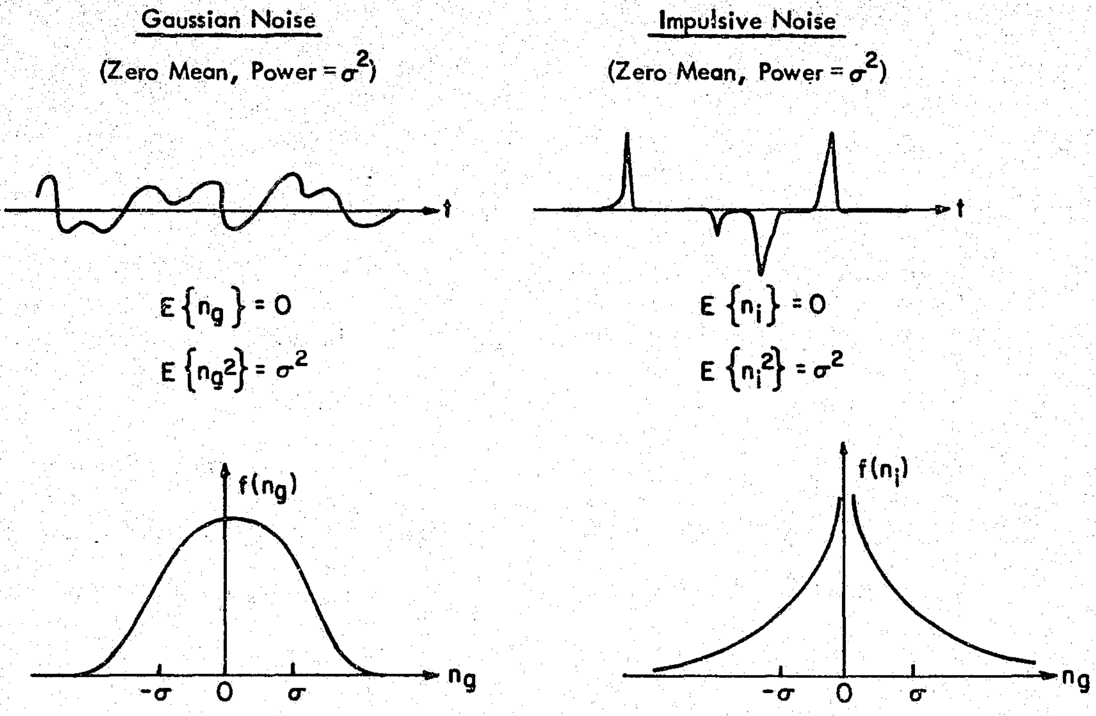


Fig. 8 Probability densities for Gaussian and impulsive noise of equal power.

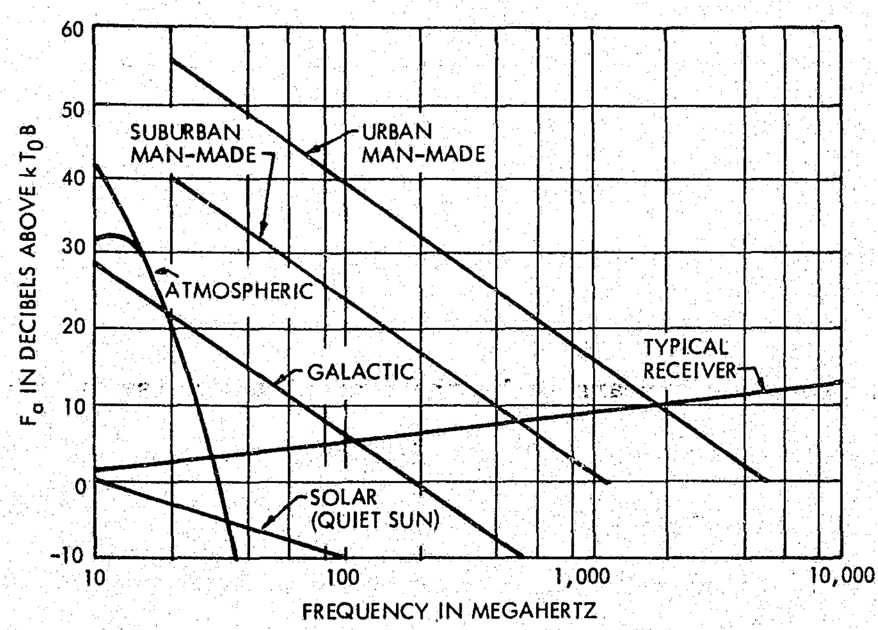


Fig. 9 Handbook values of ambient man-made and thermal noise.[47]

(also an impulsive noise) exceeds the background level of Gaussian noise below 30 MHz.

To use digital error probabilities in the design of a mobile radio transmission system it is necessary to determine the existing noise power levels and to specify signal powers which will result in acceptably low error probabilities. Rule of thumb handbook estimates such as in Fig. 9 could be used, but a more extensive analysis of ambient man-made noise in the range 200-500 MHz has been made by E.N. Skomal[21] whose summary is reproduced in Fig. 10. He has tabulated the average ambient noise power (that is, its mean square amplitude) into a matched dipole, using units of dBm (decibels relative to one milliwatt) which simplifies the issue of units and permits a quick calculation of the mean signal-to-noise ratio for error prediction.

b. Ignition noise

Being especially interested in mobile communication, we should also consider in detail the contribution of vehicle ignition interference to the ambient urban noise. The ignition spark of an automobile engine is a very short surge of high current (about 4 nanoseconds at 200 amperes)[23] which contains significant frequency components through the UHF range. Figure 11 shows that the magnitudes of the power spectral maxima of a rectangular pulse (at f = 0, 3/T2, 5/2T, ...) decrease as f^{-2} or at -20 dB/decade. It is reassuring to note that the handbook curves for urban and suburban man-made noise of Fig. 9 decrease at -23 dB/decade, supporting the claim that man-made noise is indeed impulsive.

In order to measure the amount of radiated ignition noise, detailed measurement procedures have been established by the SAE[24] and the IEEE[25].

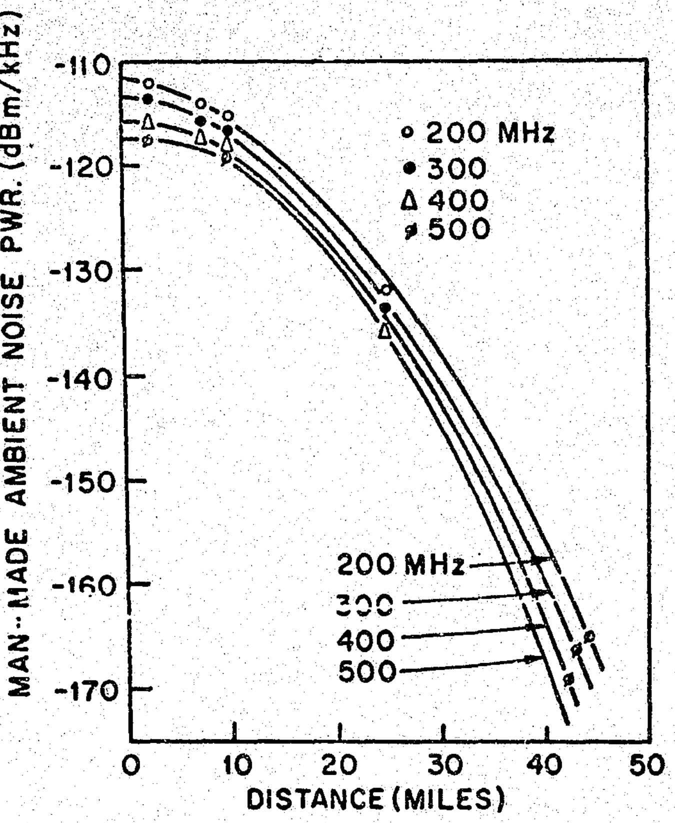


Fig. 10 Ambient Man-Made Radio Noise within 50 miles of Metropolitan Areas[21]

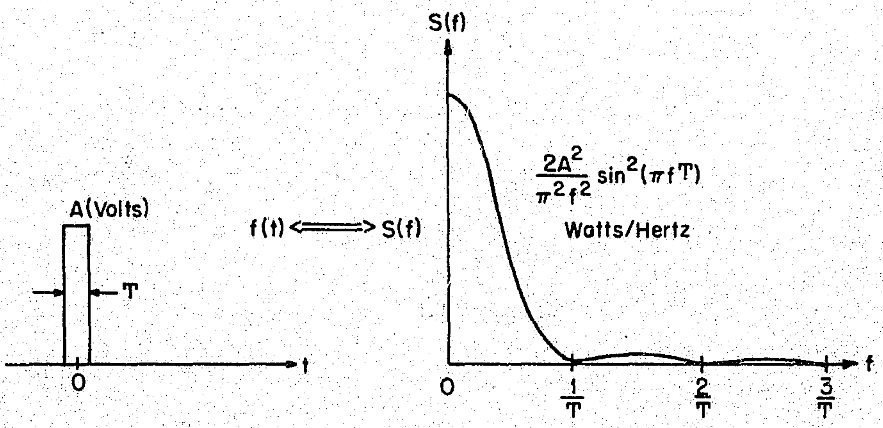


Fig. 11 Pulse Power Spectral Density

From several sources, McCoy[22] has assembled measurements of urban radio noise and rescaled them to dBm/kHz, as in Fig. 12*. It is not clear that ignition noise was the only noise component present in these measurements, however it probably was the predominant one. Assuming this to be the case, the curious shape of those curves may be due to both resonances in the vehicle's body and chassis wiring (a frequency-selective system response) and/or to power spectral variations in the short ignition pulse (non-white driving input). For example, the noise minimum at 400 MHz implies an ignition pulse duration of 1/400 MHz = 2.5 nanoseconds, which is close to Schildknecht's cited value of 4 nanoseconds.

These peak noise measurements (i.e., the maximum instantaneous noise power) are considerably higher than Skomal's ambient levels. However, the peak power of an impulsive noise distribution may be 40 dB above its mean power (see Fig. 13). If this is taken into account, these ignition measurements are comparable to the ambient level of urban man-made noise.

3. Impulsive noise models

The statistical analysis of impulsive noise has grown from two starting points and the two resulting models, although similar, are not identical. The first model, the "telephone" model, was developed at the Bell Telephone Laboratories[12] to describe the amplitude probability distribution (APD) of impulsive telephone switching noise. Only the amplitude distribution is important in digital transmission because the time spacing between telephone noise pulses is much greater than modem tone periods so the "phase" of the noise was assumed to be uniformly distributed between 0 and 2π; similar arguments apply to digital mobile radio communication

---

*$\text{dBm/kHz} = 74.5 + 20 \log_{10} E(\mu V/m) - 20 \log_{10} f_{MHz}$

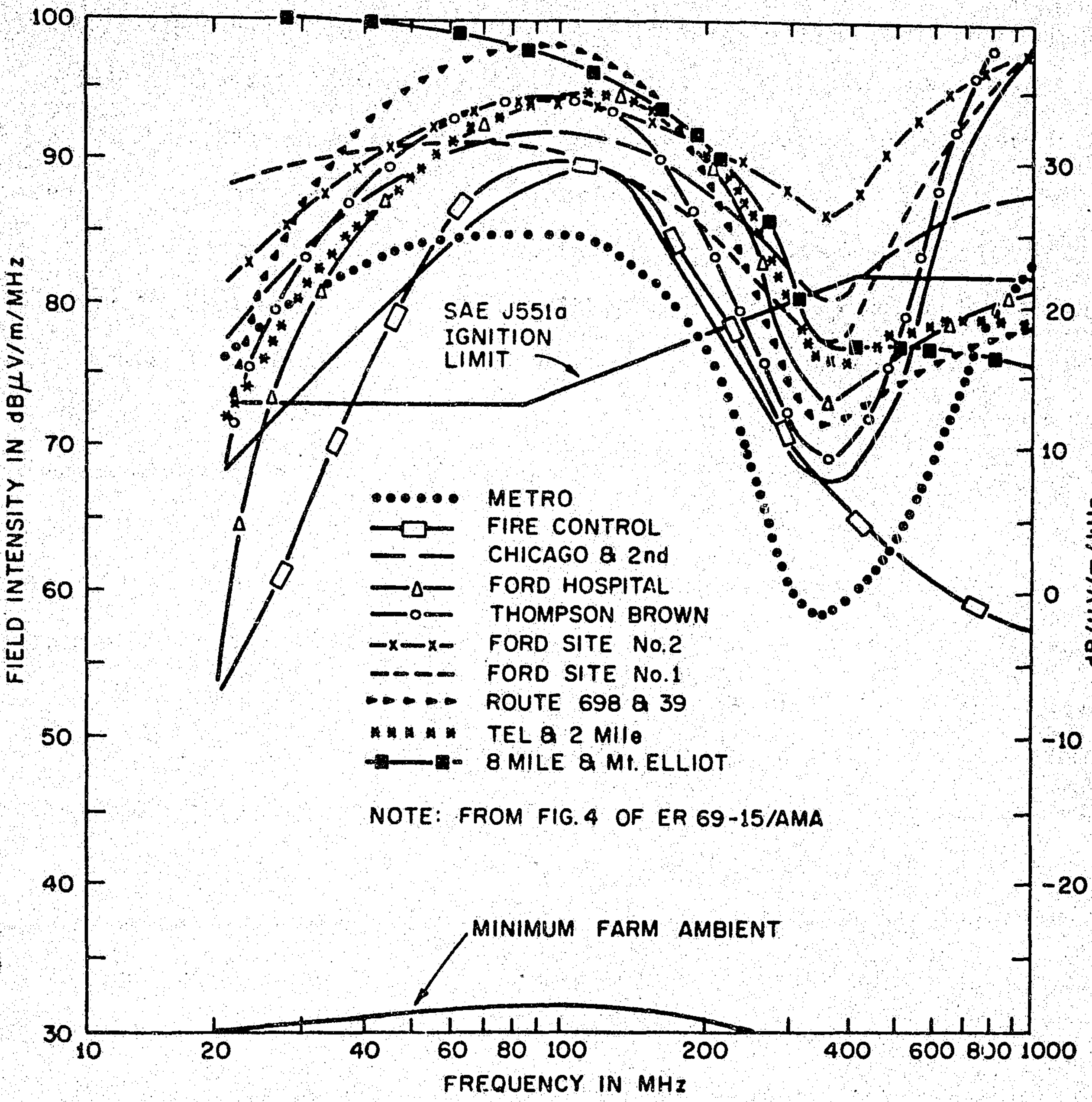


Fig. 12 Measured Radio Noise in Detroit[22]

and man-made radio noise. The telephone model is a two-parameter hyperbolic density function whose parameters can be adjusted to the average power and "impulsiveness" of an observed noise sample.

The second model, the "atmospheric" model, was developed at the National Bureau of Standards[13] to describe the amplitude distribution of radio noise "crashes" (e.g., lightning) which interfere with ionospheric radio communication. This model is also a two-parameter model, but it is a "power Rayleigh" model, so-called because the Rayleigh distribution may be obtained by a particular choice of model parameters ($k = E(x_o)$, $a = 2$).

Both the telephone and atmospheric models are summarized in Table 1. The derived parameter Vd in Table 1 is, admittedly, unmotivated, but it is suggested as a convenient measure of the "impulsiveness" of a noise distribution. It is also independent of the average noise power of the distribution. The reverse problem is: given Vd, calculate a and m. Typical values are given in Table 2.

Bruckert and Sangster[14] fitted the telephone model to man-made noise measurements at 150 and 450 MHz and obtained the following parameter values:

Frequency Band	Parameter	Value
150 MHz	m	2.481
	h	1,81 μvolt
450 MHz	m	4.004
	h	2.62 μvolt

The parameter Vd cannot be calculated for the 150-MHz values above because m is less than 3. However Vd and $E(x^2)$ can be calculated for the 450-MHz values and are 6 dB and -98.6 dBm, respectively.

Table 1

Impulsive Noise Models

	Atmospheric Model	Telephone Model
Amplitude distribution, (APD), Prob $(y \geq x)$ =	$\exp\left[-\left(\frac{x}{K}\right)^{a}\right]$	$\left[\frac{h}{x+h}\right]^{m-1}$
Amplitude density $f(x)$ =	$\frac{a}{x}\left(\frac{x}{K}\right)^{a} \exp\left[-\left(\frac{x}{K}\right)^{a}\right]$	$\frac{m-1}{h}\left(\frac{h}{x+h}\right)^{m}$
First moment,* $E(x)$ =	$K\Gamma(1 + 1/a)$	$h(m-1)\left(\frac{1}{m-2} - \frac{1}{m-1}\right)$
Second moment, $E(x^2)$, average power =	$K^2\Gamma(1 + 2/a)$	$h^2(m-1)\left(\frac{1}{m-3} - \frac{2}{m-2} + \frac{1}{m-1}\right)$
$Vd = \left.\frac{E(x^2)}{E(x)^2}\right\rvert_{db}$ =	$10 \log_{10}\left[\frac{\Gamma\ (1+2/a)}{\Gamma^2(1+1/a)}\right]$	$10 \log_{10}\left[\frac{\frac{1}{m-3} - \frac{2}{m-2} + \frac{1}{m-1}}{(m-1)\ \left(\frac{1}{m-2} - \frac{1}{m-1}\right)^2}\right]$

---

* $\Gamma(x)$ is the gamma function = $\int_0^\infty e^{-r} r^{x-1} dr$.

Table 2

"Impulsiveness" Model Parameters

Vd, dB.	Telephone (m)	Atmospheric (a)
0	undefined	infinite
2	undefined	1.2621
3	infinite	1.0024
4	6.9072	0.7440
6	4.0102	0.5866
8	3.4674	0.4874
10	3.2560	0.3880
12	3.1541	0.3532
14	3.0986	0.3064
16	3.0935	0.2793
18	3.0885	0.2554
20	3.0834	0.2361
infinity	3.0000	0.0000

Figure 13 shows measurements for atmospheric and man-made noise taken from Matheson.[54] The values of Vd have been calculated as 16 dB and 14 dB, respectively, and are shown on the curves. The similar shapes of these distributions and the nearly equal values of Vd indicate that atmospheric and man-made noises are similarly distributed "impulsive" noises.

The choice between the atmospheric or telephone APD models for man-made UHF/VHF radio noise is a matter of modeling judgement; it is less important to dwell on their differences than to note their similarity as contrasted with the Gaussian noise distribution (see Fig. 14) and to realize that either model may adequately describe man-made impulsive noise distributions for digital error calculations. In this research report the atmospheric model will be emphasized due to the larger body of literature which deals with the atmospheric model. Also, the nominal value of 6 dB will usually be assumed for Vd but, when possible, comparisons will be made with the telephone model and/or with Vd = 16 dB to test slightly different degrees of "impulsiveness".

C. Calculation of Error Probabilities

The calculation of error probabilities for binary-encoded signals in the presence of noise is not a difficult process if one uses the simple geometrical techniques of G. Franklin Montgomery.[18] His fluctuation noise is simply zero-mean Gaussian noise, leading to the error curves of Fig. 15 which should be compared with the similar curves of Fig. 6.* But these same techniques are also valid for any non-Gaussian noise amplitude statistic and several authors[15,16,17] have indeed calculated binary error probabilities for various digital modulations in impulsive noise (using the atmospheric model) for both fading and non-fading signals as shown below.

---

*On page 19.

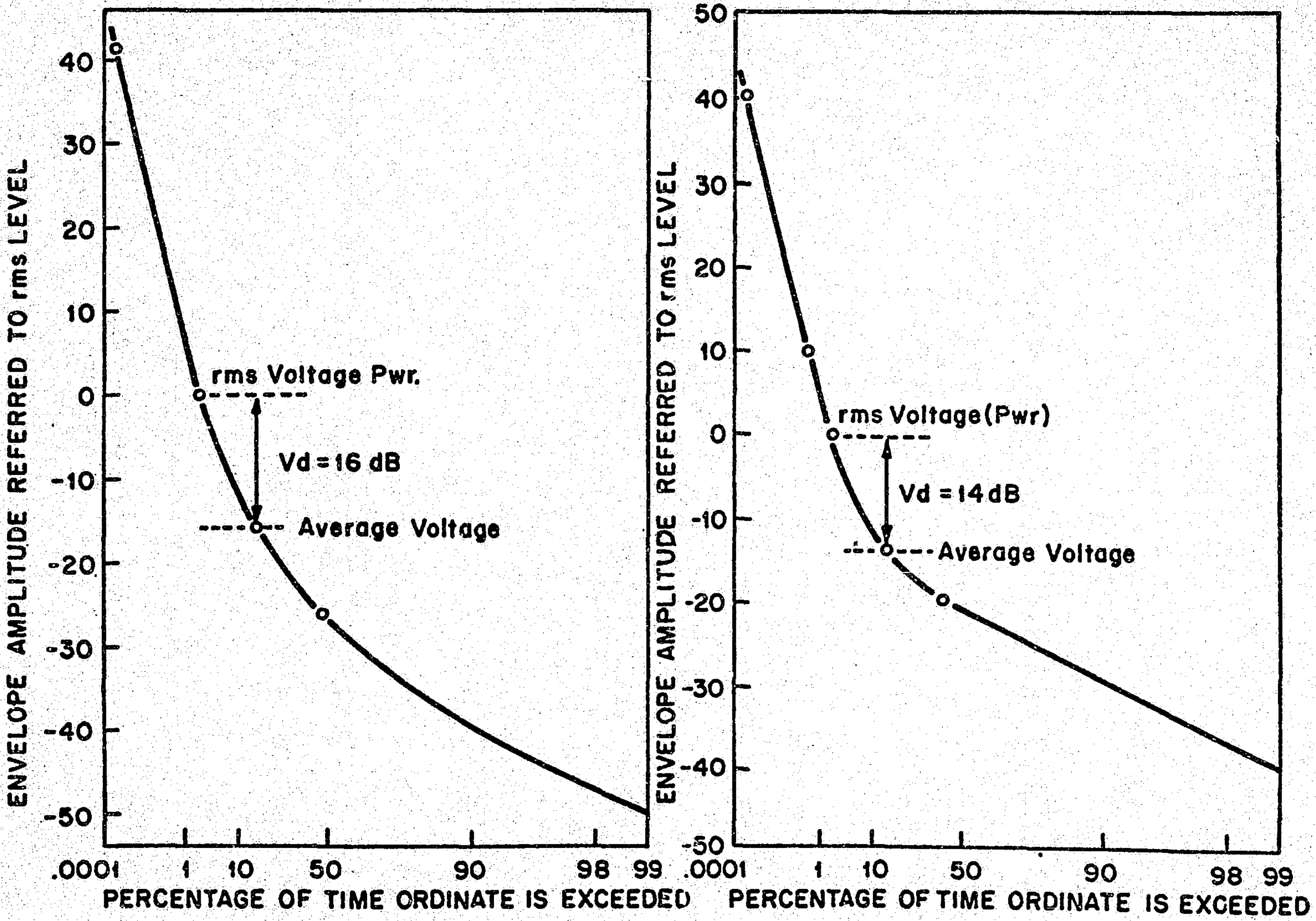


Fig. 13 Amplitude probability distributions for atmospheric radio noise (left) and man-made noise (right)[48]

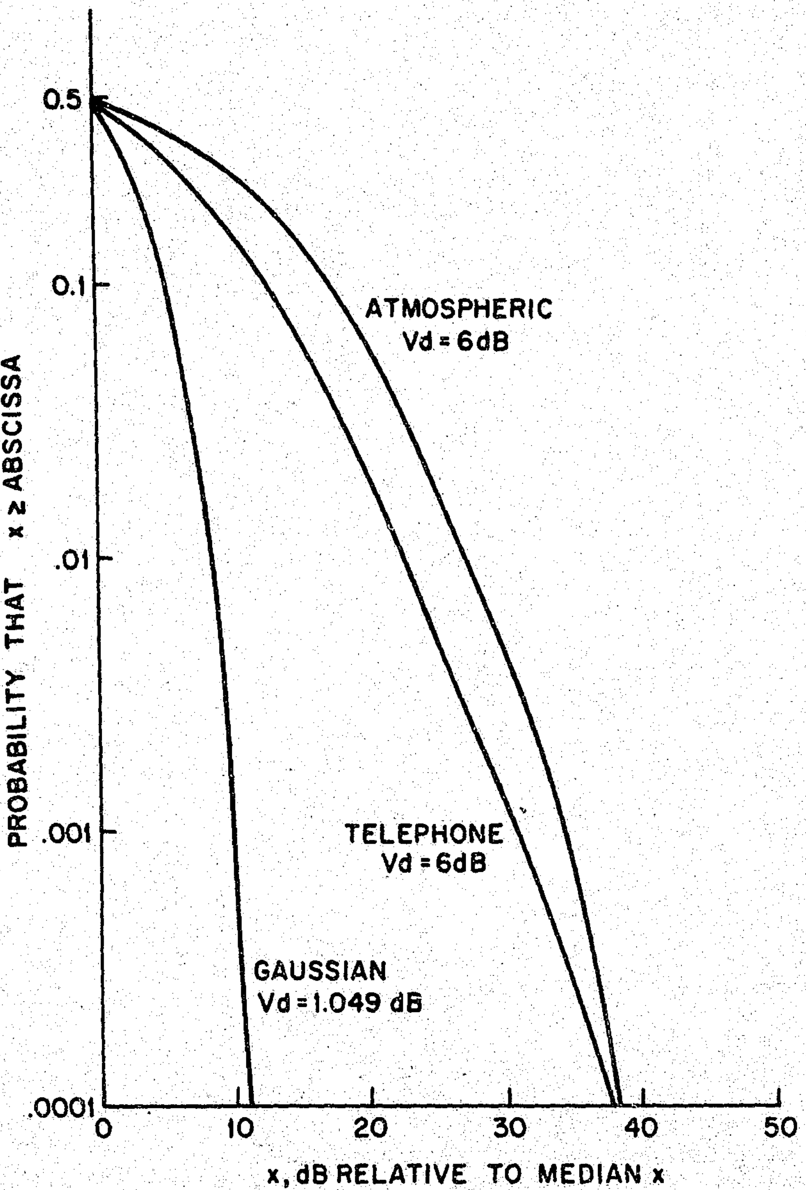


Fig. 14 Amplitude probability distributions for Gaussian, telephone, and atmospheric models.

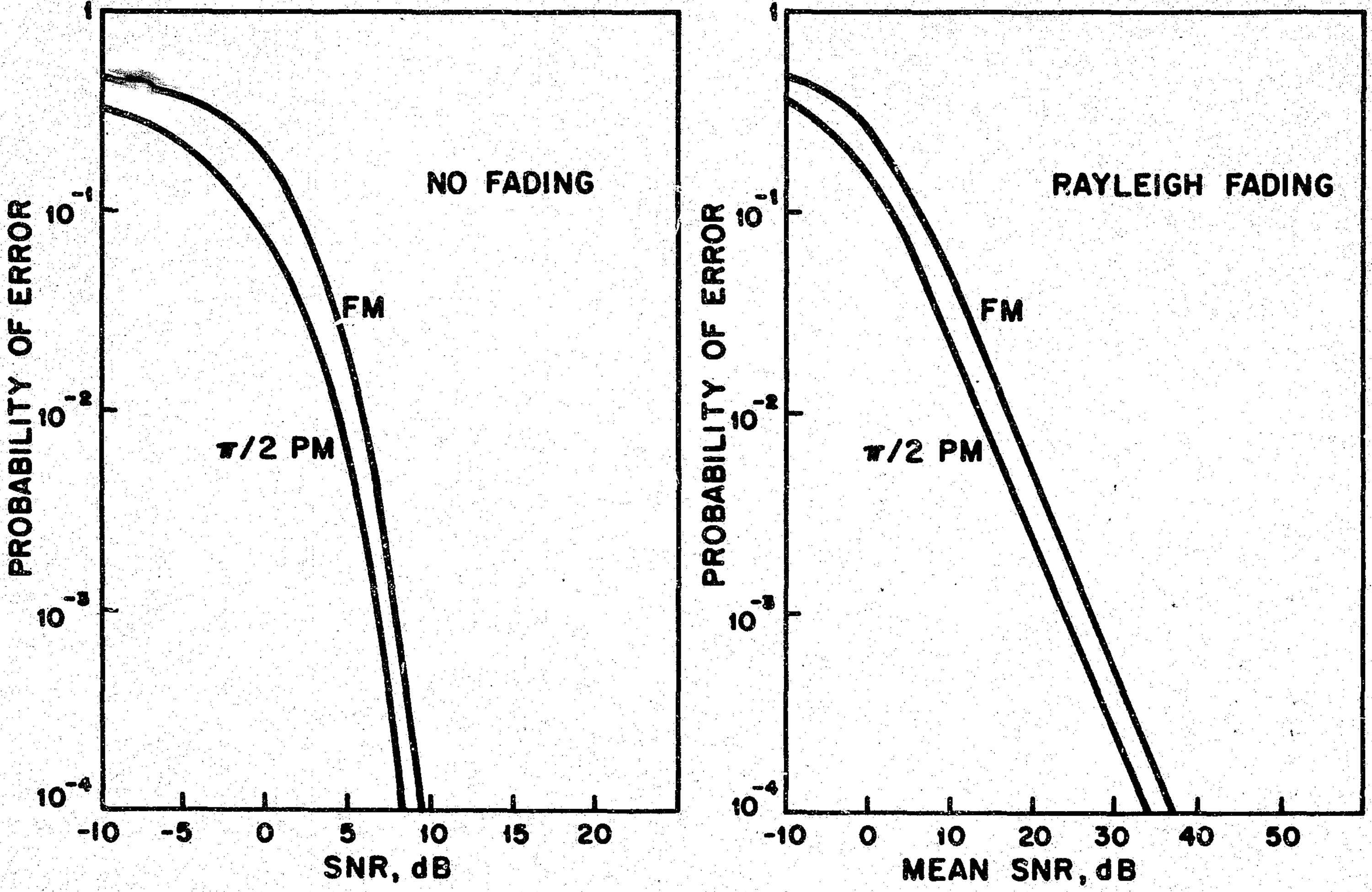


Fig. 15 Probability of binary error for fading and non-fading signals. FM is ideal noncoherent FSK; PM is ideal PSK.[18]

Modulation	Fading?	Non-Fading?	Vd, dB	Reference
PSK	yes	yes	6	15, 17
DPSK	yes	yes	6	17
FSK	yes	no	1 to 10	16

To complete these results for all three modulations, the simple case of an FSK signal (both fading and non-fading) in impulsive noise has been evaluated by the author. Its explicit solution allows us to compare the atmospheric and telephone models with respect to error predictions and to investigate the relative effects of "impulsiveness" (as measured by Vd) and Rayleigh signal fading on error probability.

Montgomery states[18] that no error can occur in FSK modulation so long as the signal amplitude exceeds the noise, but that errors will occur with probability 1/2 whenever the noise amplitude exceeds the signal. Adopting Montgomery's notation:

FSK non-fading

s_o	signal amplitude (constant)
s_o^2	signal power (constant)
N	instantaneous noise amplitude
N^2	instantaneous noise power
N_o^2	average noise power = $E(N^2)$
$F(N')$	probability $N \geq N'$ (noise APD of Table 1)
P_e	probability of binary error

Using this notation, the expressions for $P_e(S_o)$ and SNR are shown on the next page:

$$P_e(S_o) = \frac{1}{2}F(S_o) = \frac{1}{2}e^{-(S_o/k)^a} \qquad \text{atmospheric model}$$

$$= \frac{1}{2}\left[\frac{h}{S_o+h}\right]^{m-1} \qquad \text{telephone model}$$

$$\text{SNR} = \left[\frac{S_o}{N_o}\right]^2 = \frac{S_o^{\,2}}{k^2\Gamma\,(1+a/2)} \qquad \text{atmospheric model}$$

$$= \frac{S_o^{\,2}}{h^2(m-1)\left[\frac{1}{m-3} - \frac{2}{m-2} + \frac{1}{m-1}\right]} \qquad \text{telephone model}$$

These values of P_e are plotted against SNR in Fig. 16 for both the telephone and atmospheric models (Vd = 6 dB, m = 4.0102, a = 0.5866 from Table 2, and in Fig. 17, for Vd = 16 dB (m = 3.0935, a = 0.2793).

FSK Rayleigh fading

s	instantaneous signal amplitude
$S_o^{\,2}$	mean signal power
$\overline{P}_e$	average P_e

$f(S)$ Rayleigh probability density $= \dfrac{2S}{S_o^{\,2}}\,e^{-(S/S_o)^2}$

$$\overline{P_e} = \int_0^\infty f(S)P_e(S)\,dS$$

$$= \frac{1}{2}\int_0^\infty \frac{2S}{S_o^{\,2}}\,e^{-(S/S_o)^2}\,F(S)\,dS$$

$$\overline{P_e} = \frac{1}{S_o^{\,2}}\int_0^\infty S e^{-(S/S_o)^2}\,F(S)\,dS$$

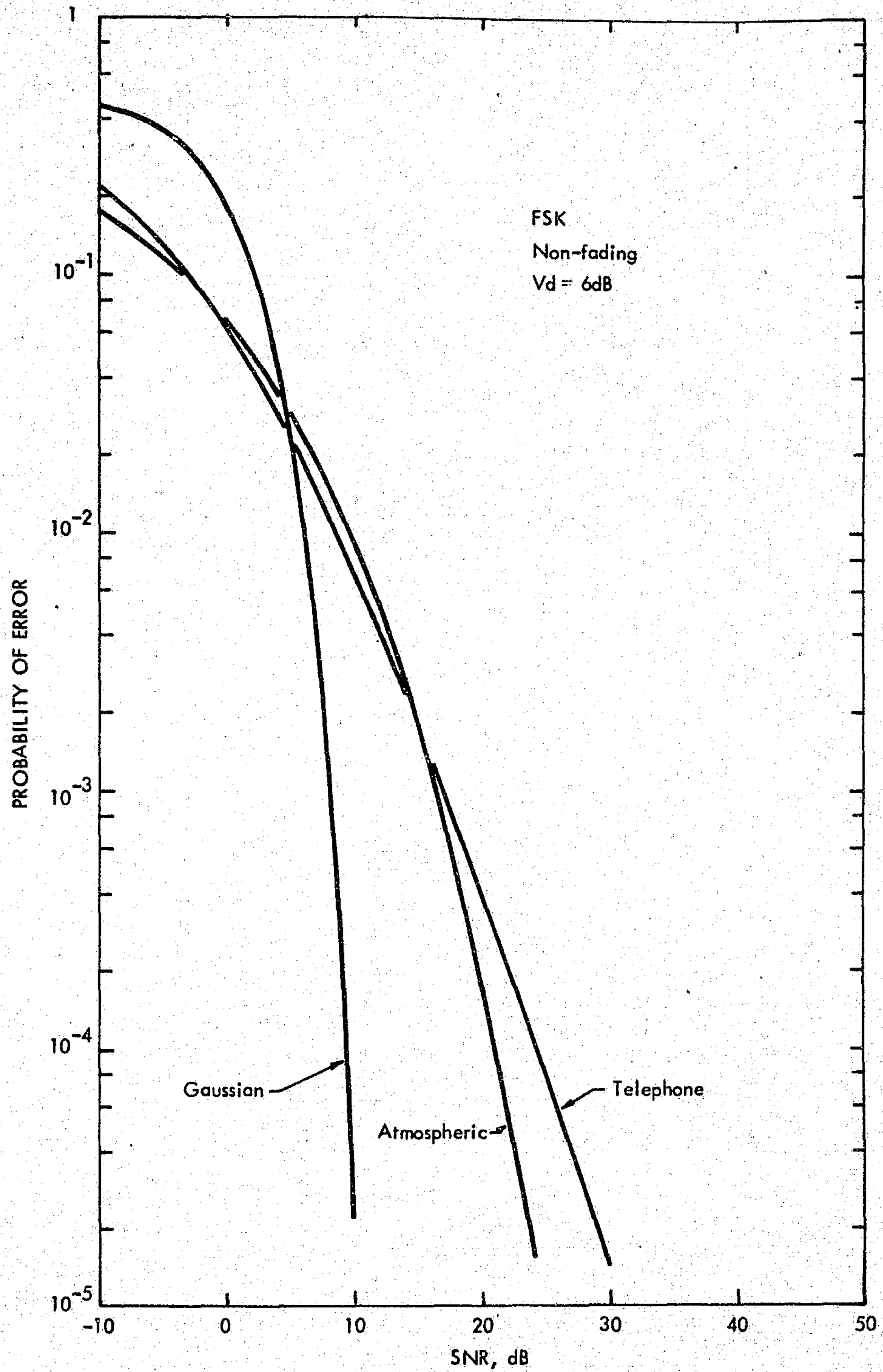


Fig. 16 Probability of binary error for FSK modulation in impulsive noise (non-fading, Vd=6 dB).

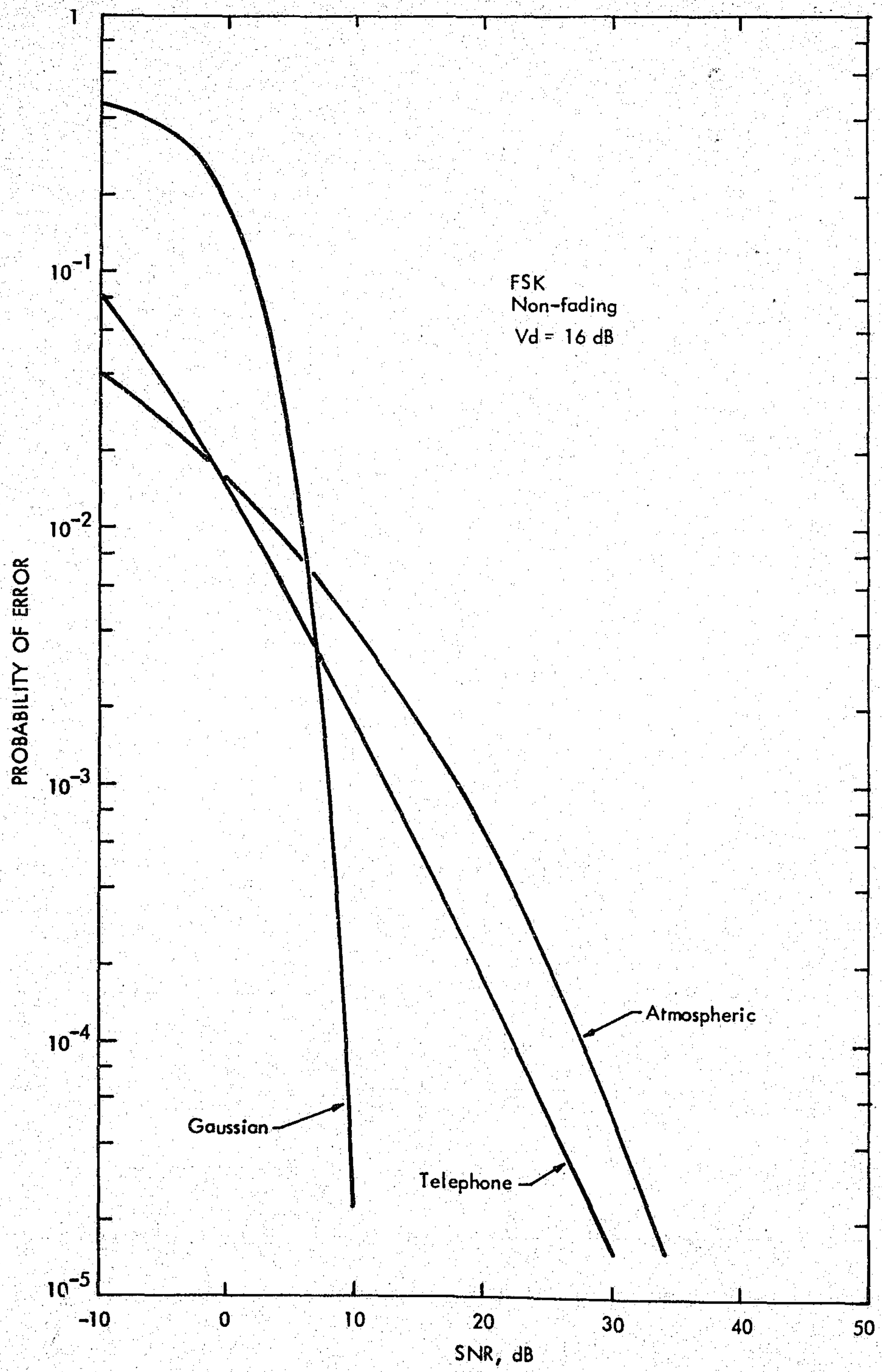


Fig. 17 Probability of binary error for FSK modulation in impulsive noise (non-fading, Vd=16 dB).

For the FSK Rayleigh fading case, it was necessary to numerically integrate to obtain the error curves of Fig. 18 (Vd = 6 dB) and Fig. 19 (Vd = 16 dB). Conda's curve for fading FSK signals in impulsive noise (Vd = 6 dB) is also plotted in Fig. 18 for comparison.

J.H. Halton and A.D. Spaulding[20] have also performed similar fading and non-fading calculations for both FSK and DPSK modulations using the atmospheric model (Vd = 6 dB) and their results are replotted in Fig. 20 (non-fading) and in Fig. 21 (fading).

D. Summary

From Figs. 16 through 21 it is possible to recognize some general characteristics of digital error probabilities:

(1) in the absence of Rayleigh fading, the signal-to-noise ratio (SNR) required for a "low" binary error probability (in the range of 10^{-4} to 10^{-5}) is about 20 dB greater for impulsive noise than it is for an equal Gaussian noise power (see Figs. 16 and 17);

(2) in the presence of Rayleigh fading, the error probability curve for Gaussian noise shifts so as to require as much as a 30-dB increase in SNR compared to a much smaller increase (about 10 dB) for impulsive noise; and the two binary error probability curves become almost identical (see Figs. 18 and 19);

(3) the error performances predicted by either the atmospheric or telephone models for impulsive noise are so similar (at least for FSK modulation) that there is little incentive to determine which is the "better" model of impulsive noise

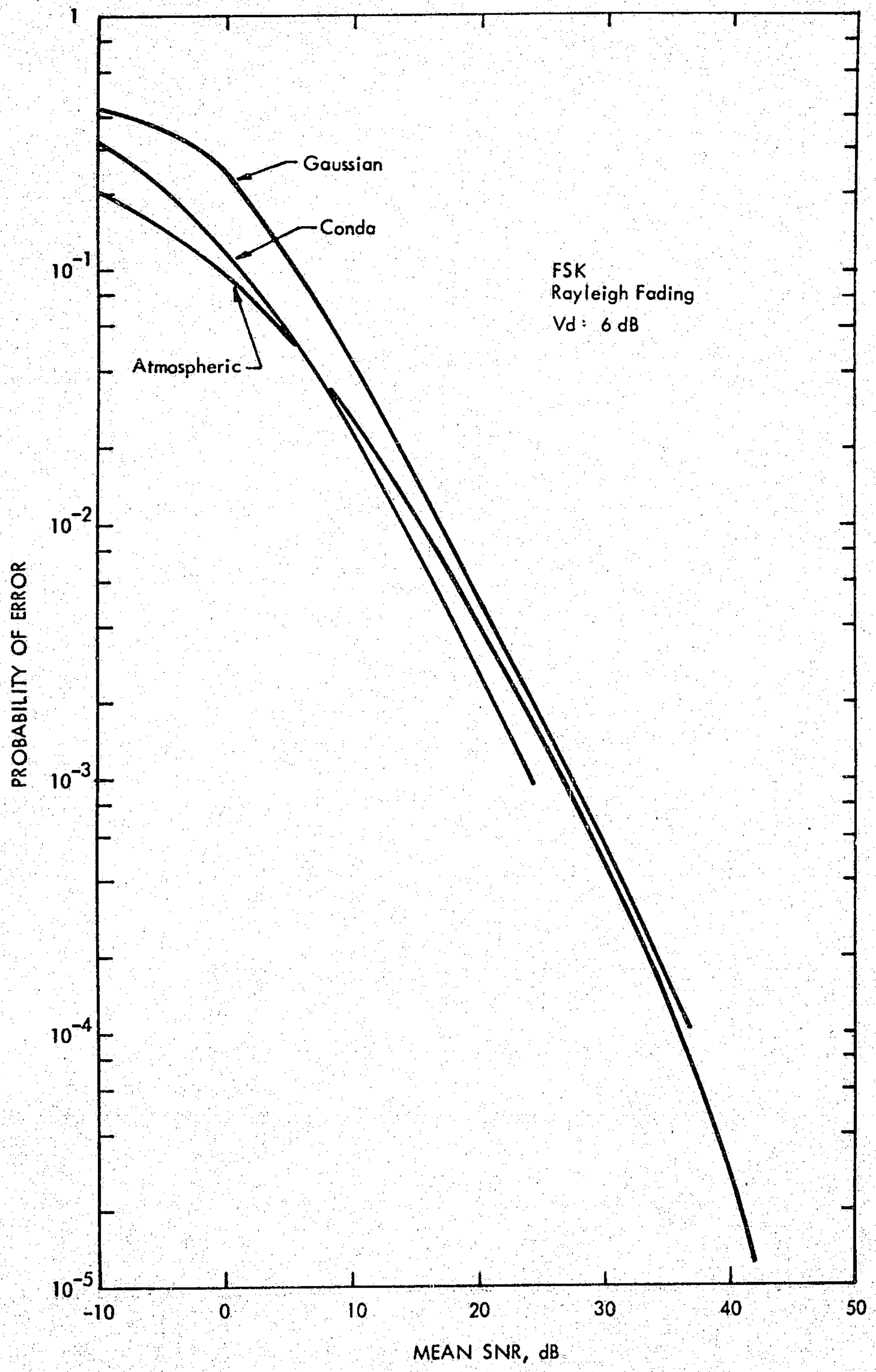


Fig. 18 Probability of binary error for FSK modulation in impulsive noise (Rayleigh-fading, Vd=6 dB).

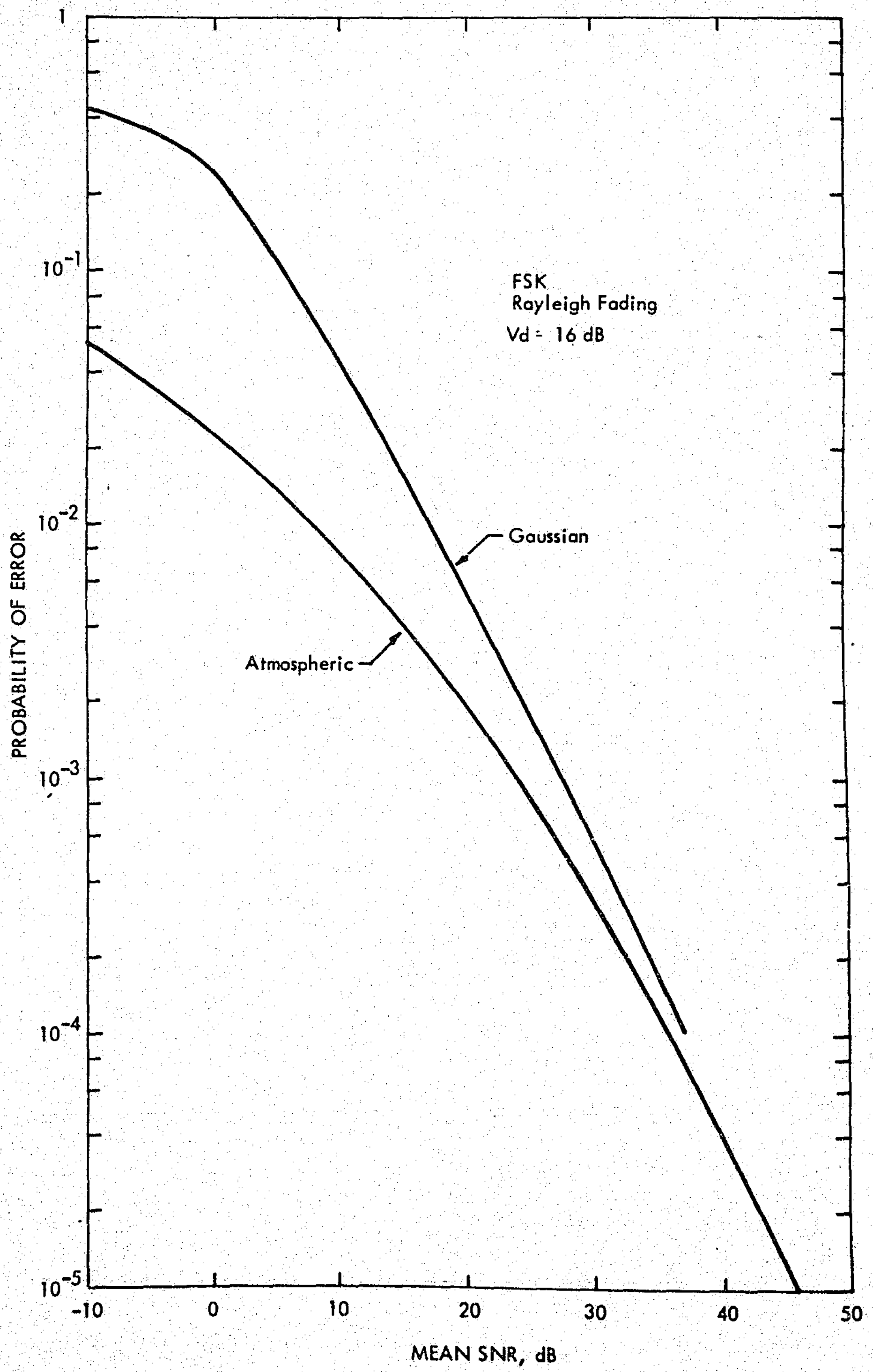


Fig. 19 Probability of binary error for FSK modulation in impulsive noise (Rayleigh-fading, Vd=16 dB).

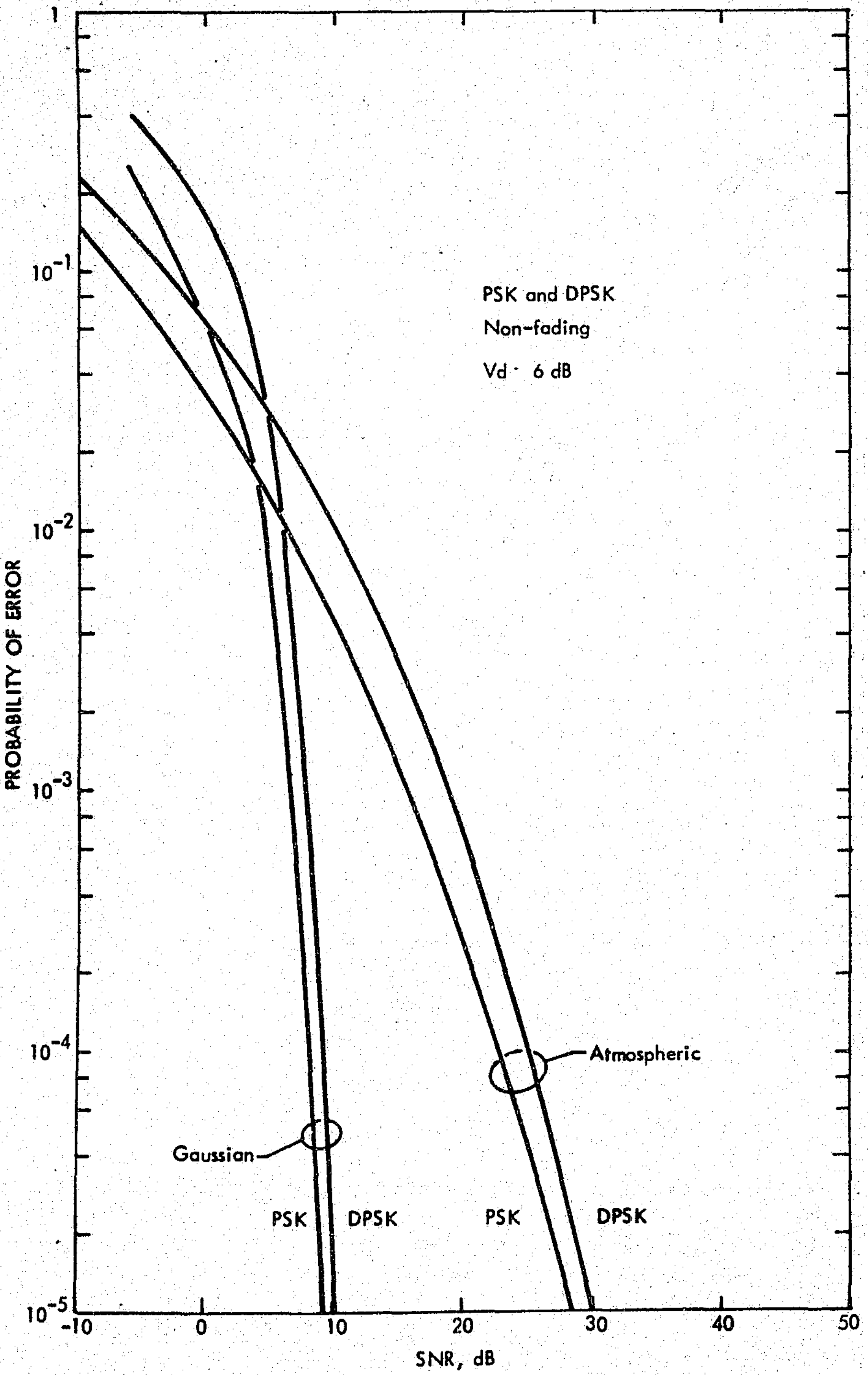


Fig. 20 Comparison of Binary Error Probabilities for Gaussian and Impulsive Noise in the Non-Fading Case (PSK and DPSK Modulation).[15,16,17]

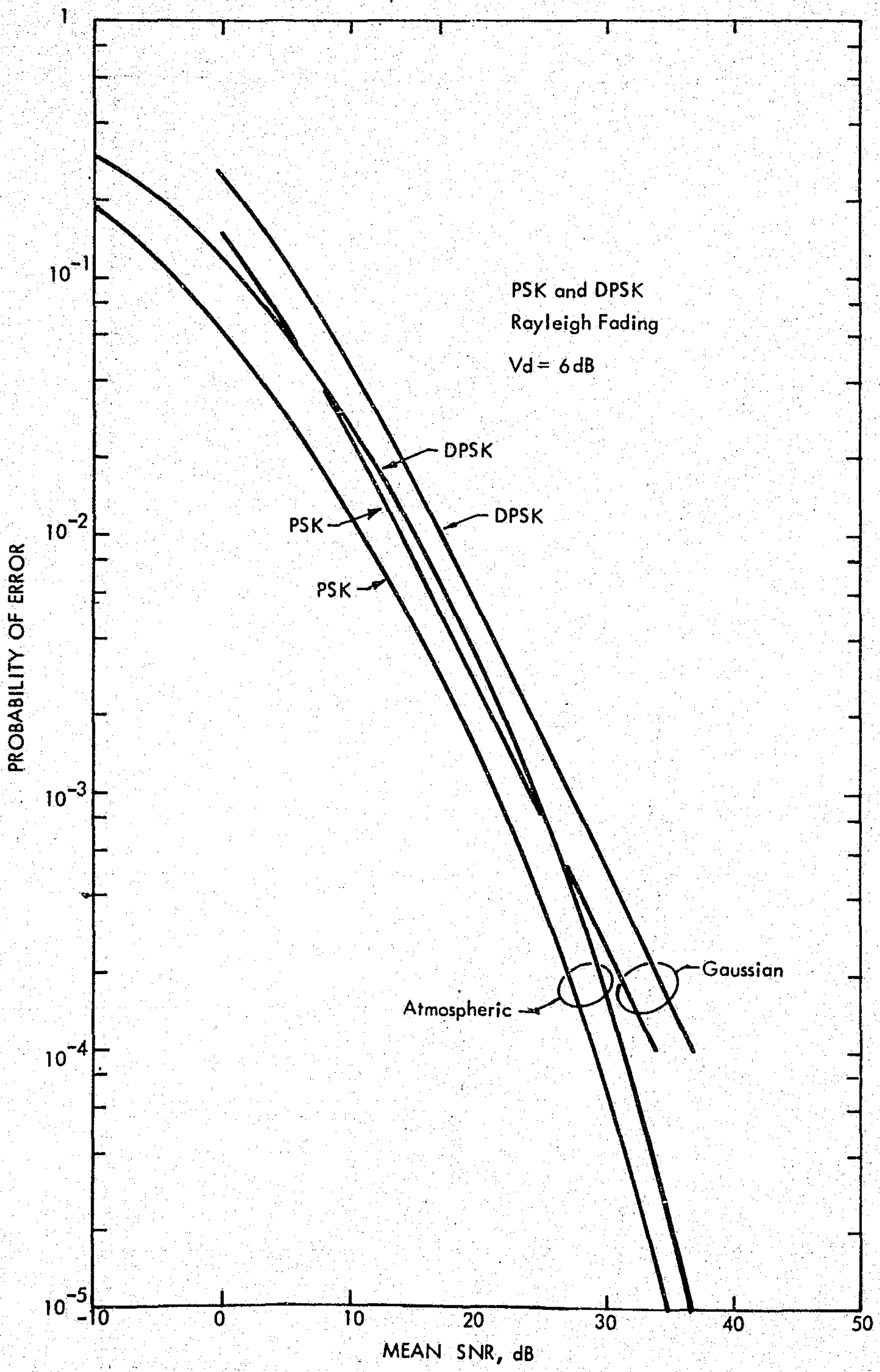


Fig. 21 Comparison of Binary Error Probabilities for Gaussian and Impulsive Noise in Rayleigh Fading (PSK and DPSK Modulation).[15,16,17]

(see Figs. 16 and 17);

(4) the FSK error probabilities for impulsive noise do not seem to be affected by an increase in "impulsiveness", Vd, from 6 dB to 16 dB, apparently being more sensitive to this type of noise distribution per se than to the relative degree of "impulsiveness" (compare Figs. 16 and 17);

(5) whenever there is fading, a mean signal-to-noise ratio of at least 40 dB is necessary to obtain "low" probabilities (10^{-4} to 10^{-5}), compared to a SNR of 30 dB in the impulsive, non-fading case and of only 10 dB in the Gaussian, non-fading case (see Figs. 16 and 18, 20 and 21).

(6) thus if fading could be effectively eliminated by some form of diversity (see Chapter IV), a reduction of 10 dB in required SNR could be achieved, or better error performance could be achieved at the same SNR.

CHAPTER 3

EXTERNAL FACTORS

This chapter brings together a few of the non-technical factors that affect the design of digital mobile radio systems. Economic factors are considered first, then the question of spectrum utilization, and finally the characteristics of conventional voice FM equipment for digital use are discussed. Each of these factors will indirectly affect the technical designs of Chapter 4.

A. Economic Factors

The economic factors which are considered here cannot be intimately related to costs--prices change too rapidly in the electronics market for that--but they are related to the structure of mobile radio equipment (transmitter power/cost ratios) and the fact that there are many more mobiles than base stations (the "times N" factor).

The first economic factor is the curious shape of the transmitter power/cost curve, shown in Fig. 22. Based on 1972 list prices for base and mobile FM transceivers in the low-VHF, high-VHF, and UHF bands, these figures show that through the 100-watt power range for mobile transceivers and the 400-watt range for base equipment, costs are almost constant and independent of transmitter power. Above these powers there has not been enough production experience to justify a prediction of cost for very high power equipment. These figures show that with the present price structure, mobile radio signal power is almost "free" over a wide range for the power levels shown, and that a design goal of minimizing signal power would not yield the same savings in mobile radio communication that have been realized, for instance, in minimiz-

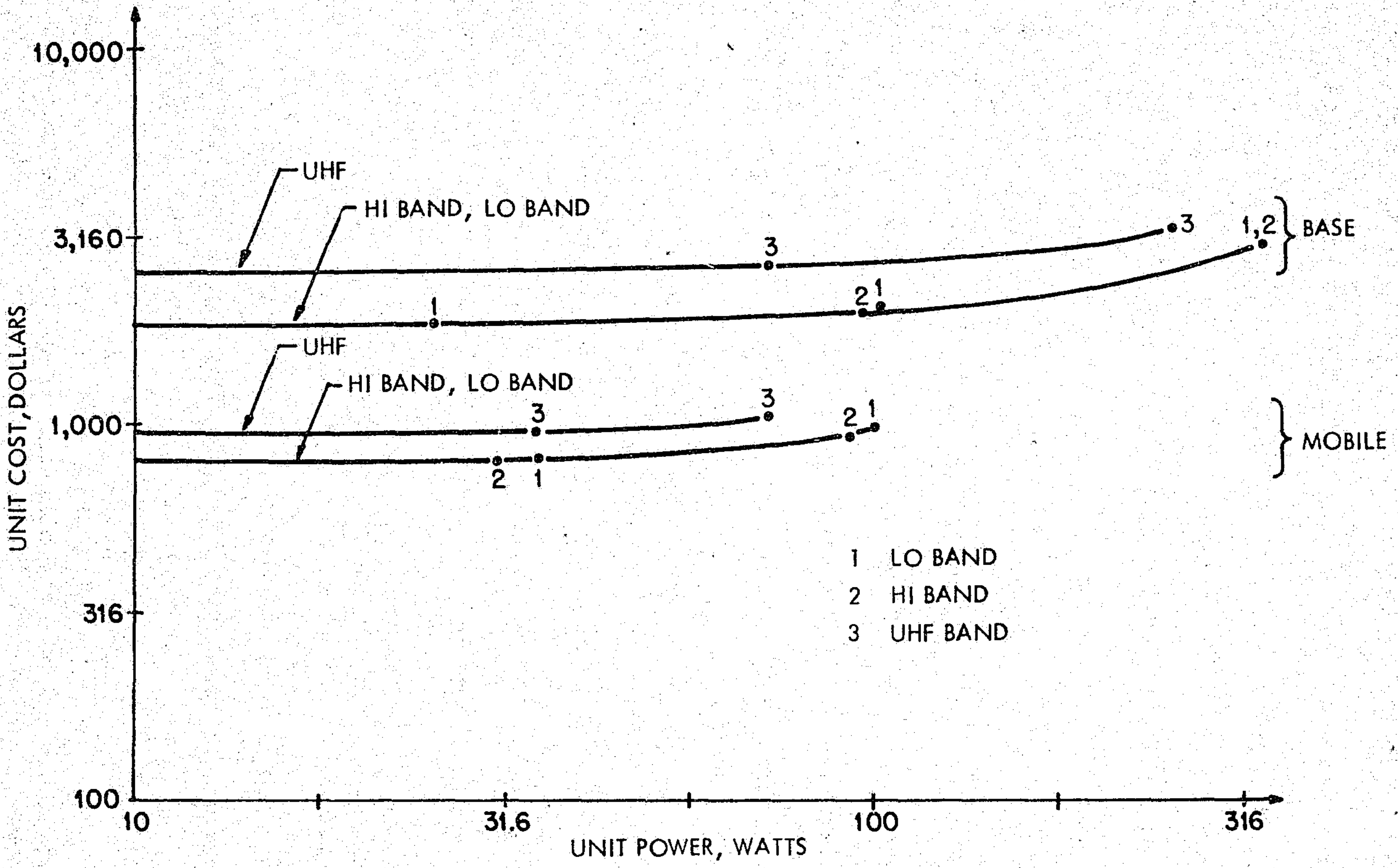


Fig. 22 Cost Versus Power for Base and Mobile Radio Equipment

ing communication power (and, therefore, weight) for spacecraft.

The "times N" factor represents the fact that in the classic mobile radio system with one base station and N mobiles the economic strategy is to concentrate as much as possible of the necessary cost at the base station, so long as, for the same level of performance, the cost of the individual mobile's equipment is more than 1/N of the alternate cost for base station equipment. This is especially true when the number of mobiles become quite large as in many large police departments or taxicab companies. When N becomes even larger yet, as in the "one man, one radio" systems which have been projected,[26] the "times N" factor would seem to call for mobile units of minimum complexity that could be standardized and mass produced at very low cost. On the other hand, techniques to improve the radio channel for digital transmission (diversity reception, for example) and to improve spectrum utilization (multichannel trunking, high-speed digital signalling, etc.) tend to increase the complexity of mobile units, and therefore their cost. Thus the tradeoffs between cost and performance must be continuously examined as technology advances.

B. Spectral Utilization

It is quite well known that there has been a shortage of available land mobile spectrum, especially in large metropolitan areas, and that this fact has been of growing concern to users and the FCC alike over the last 15 years. Quoting from the FCC Annual Reports:[27]

1958: "... the Commission's objective is ... to relieve, to the greatest extent possible, the frequency congestion that prevails in most of these services.

1962: "The various industrial services grow within the confines of a very small portion of the usable radio spectrum. This situation has led to extremely congested operating conditions in many areas.

1964: "One of the most pressing problems faced by the Commission is to find frequency relief for the public-safety, industrial and land-transportation radio services. These land mobile radio operations have grown in the past few years and frequency shortage has become acute in many geographic areas.

1966: "The major problem facing the Land Mobile Radio Services, as well as one of the thorniest confronting the Commission, is the congestion in the limited spectrum space available to these intensively populated services."

The FCC acted in 1971 to alleviate the short-term need for additional channels by permitting land-mobile use of up to two UHF television channels in the 470- to 512-MHz band in each of 10 metropolitan areas (e.g., Channels 14 and 16 in Boston and Channels 14 and 15 in New York) on a "not to interfere" basis with television reception in neighboring metropolitan areas (FCC Docket 18231). As of a year later (September 1972), only about 35 applications for the 470-512 band had been received by the FCC, and about 30 licenses granted,* but use of this new allocation is expected to accelerate. The long-term response, also in 1971, was the permanent allocation of 115 MHz of spectrum (808-902 and 928-947 MHz), to land mobile use, as compared with only 40 MHz in the existing mobile bands combined. The exact subdivisions of the 900-MHz allocation as between private systems and common carriers are still under study (Docket 18262), as are a number of technical issues such as the use of geographical frequency reuse (cellular) systems. While it will take some time to exploit the 900-MHz band, the 3:1 increase in total land-mobile radio spectrum would appear to meet foreseeable needs for mobile communication.

In addition to the question of frequency allocation for land-mobile vis-a-vis other radio services, the FCC is equally concerned with problems of spectrum utilization in the land-mobile bands as shown by the FCC-sponsored

---

*Electronics, September 25, 1972, p. 85

study of land mobile channel occupancy in New York, Detroit, and Los Angeles,[28] by its solicitation of comments on the use of teleprinters in the land mobile services (Docket 19086), and by its present Chicago experiment in decentralization of frequency allocations between mobile services on a regional basis according to local needs rather than according to the existing national block allocation system. The Chicago Regional Spectrum Management Center is currently building a data file on all users in a 100-mile radius (based on a new and much more comprehensive license application), and monitoring actual usage on all channels as aids in future sub-allocation and assignment decisions.

Individual users, too, have long been concerned with improving channel utilization as their communications requirements have grown. The common use of short code words for frequent, low-entropy messages, such as "Roger"for "I understood your transmission", yields a 5:1 reduction in transmitted characters and similar reduction in voice transmission time. A further gain in channel efficiency has been realized by users such as the San Francisco Police Department who have experimented with digitally transmitted codes. In a digitally transmitted code the "Roger" message can be represented by one 7- to 11-bit character such as the ACK (acknowledge) character of the ASCII code. If transmission is at 110 bits/sec (teletype speed, this requires 0.1 second rather than the 1/2 second or so to say "Roger", a further improvement of 5:1 in channel utilization. At higher digital transmission speeds, say 1200 bits per second, the improvement is even more dramatic.

Digital transmission, then, permits a very rapid communication of coded messages and the important question is one of bandwidth: "What bandwidth is required for rapid digital communication"? The older answer to this question is Nyquist's channel capacity (for no intersymbol interference and no noise)

$$C_1 = W$$

where C_1 is the maximum Nyquist communication rate (bits/sec) and W is the r-f bandwidth in Hertz for double-sideband modulation. The more general result is Shannon's equation for channel capacity in the presence of white Gaussian noise

$$C_2 = \frac{1}{2} (W) \log_2 (1 + S/N)$$

where S is the mean signal power, N is the Gaussian variance (mean noise power), C_2 is the maximum Shannon communication rate (bits/sec), and W is as above. Using binary (two-level) modulation it is not possible to signal faster than Nyquist's rate of W, and maximum rate depends only on bandwidth. If, however, it is possible to use a multilevel modulation such as discrete PAM or m-ary PSK, then it is possible to exchange a high S/N ratio for reduced bandwidth or vice versa.

The exchange of bandwidth for higher signal-to-noise ratio (bandwidth exchange) is a recognized characteristic of FM modulation[30] and it is natural to wonder if digitally modulating an audio signal and then transmitting this audio signal over FM equipment ("multilevel submodulation") results in a net improvement in data rate compared to the increased bandwidth requirement of FM. Figure 23 shows graphically what Shannon proved mathematically: no modulation or submodulation "trickery" can result in a data rate greater than C_2. In Fig. 23, spectral efficiency is the Shannon channel capacity per r-f bandwidth and is measured in bits/second per Hertz. The parameter β is the modulation index. Note that increasing the modulation index to improve S/N in FM submodulation reduces rather than improves spectral efficiency because the bandwidth increases faster than $\log_2 (1 + S/N)$.

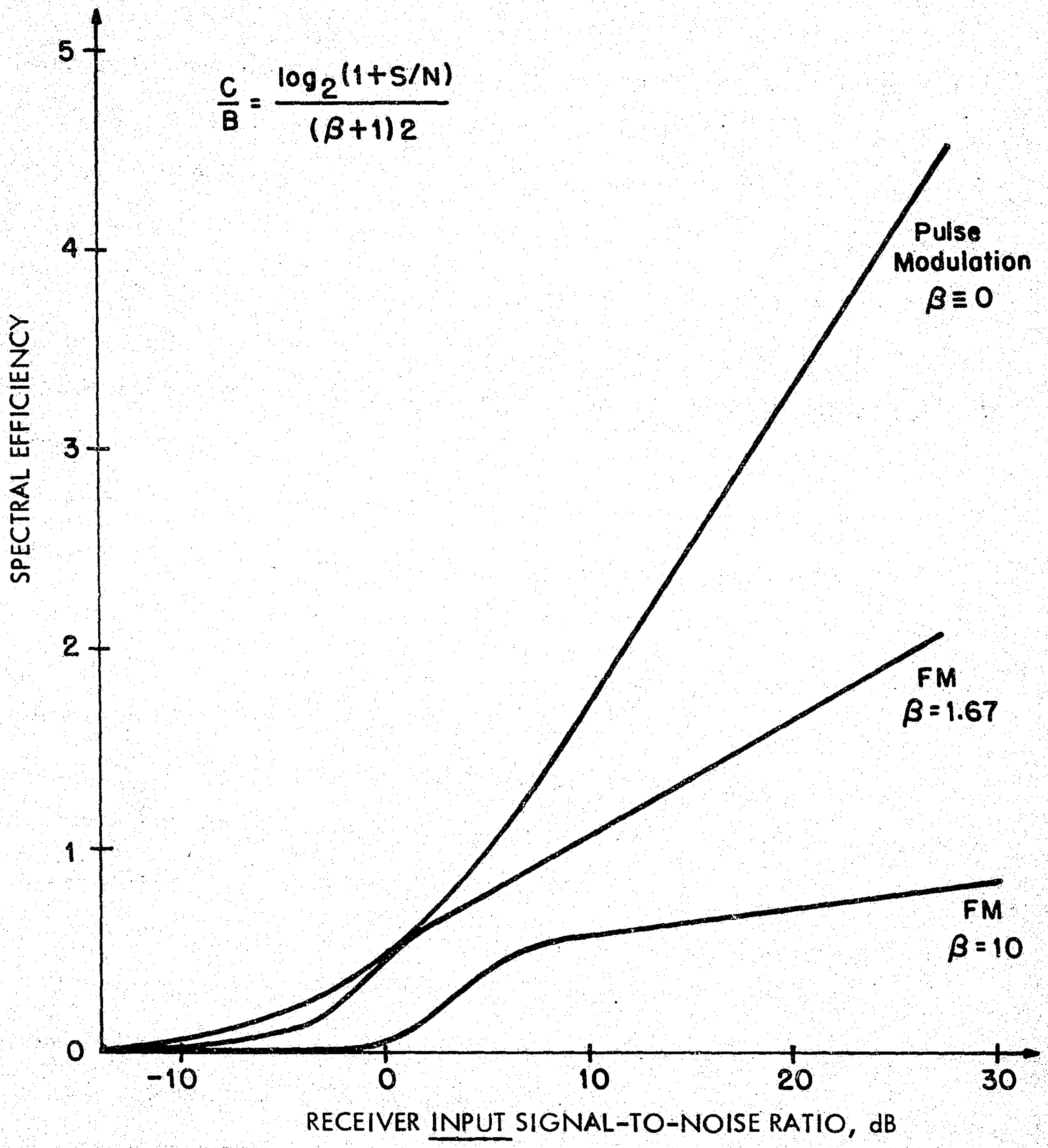


Fig. 23 Spectral Efficiency of Pulse and FM Modulations

Note also the threshold effect in FM, which rapidly reduces channel S/N, and therefore efficiency, for receiver input levels below threshold.

In mobile radio equipment designed for 25-kHz channel spacing, the second IF bandwidth in the receiver is typically 10 kHz between 3 dB points, only 40 percent of the actual channel width. Using the 10-kHz figure for W and a mean S/N of 20 dB,[31] the Shannon limit C_2 on channel rate is:

$$C_2 = \frac{1}{2} (10 \text{ kHz}) \log_2 (1 + 100) = 33{,}200 \text{ bits/sec}$$

This limiting rate is, of course, based only on Gaussian noise in **a non-fading** channel and therefore represents a goal that is unachievable in practice. It does however indicate that the rates of 100-2,000 bits per second now being used in 25-kHz land-mobile channels are far from efficient, particularly since the Shannon rate for the full 25-kHz channel is 83,000 bits/sec. Much more efficient use is made of 4-kHz telephone channels (3-kHz audio bandwidth), for which the Shannon rate is 20,000 bits/sec and rates of 9,600 bits/second are regularly achieved with multi-level coding. Although the telephone channel is much better behaved than the mobile radio channel, the desirability of better utilization of the land-mobile channel should be obvious.

A rate of 100 bits/sec over a land-mobile channel represents the same spectral efficiency as normal speech, which is equivalent to about 100 bits/sec in coded character form.* Even at this rate, channel utilization is improved somewhat over voice because of the time savings that digital addressing techniques can achieve in the base/mobile "handshaking" that must precede actual message transmission. However the goal should be to use rates of 2,000 bits/sec or higher to achieve a significant improvement

---

*(150 words/min) x (5 letters/words) x (8 bits/letter) x (1 min/60 sec) = 100 bits/sec.

(20:1) in channel utilization and reduce the need for more channels as message traffic grows.

The discussion to this point has considered digital transmission over the existing channels that have evolved for voice transmission. If it were possible to set aside higher bandwidth channels for high-speed digital transmission, there might be a net gain in spectral utilization. For example, if two adjacent 25-kHz channels could be combined and used as one channel, the r-f channel bandwidth could be 30-35 kHz with the same adjacent-channel guard bands as at present. Other things being equal, this might permit transmission of 6,000-10,000 bits per second, which would represent a utilization improvement of 50-150 percent over the same two channels used separately at 2,000-bps each. Several of the manufacturers interviewed indicated the desirability of obtaining wider bandwidth channels for high-speed digital transmission instead of constraining digital transmission to fit the existing voice-channel standards. In the long run, various classes of channels might be allocated for various speed digital services, with license fees proportional to bandwidth.

C. Digital Characteristics of FM Equipment

It might seem artificial to discuss the characteristics of regular FM voice communication equipment as it is now being used for digital transmission because, as the argument goes, "Why concern yourself with digital transmission over one specific type of radio system, especially a system which has been optimized for voice, not digital, communication?" The reasons are simple. First of all, FM radio systems are in widespread use and the field testing of novel digital devices is facilitated if those devices are able to operate in conjunction with FM voice equipment; also, existing FM systems can be found operating under almost any desired test condition. The flexibility of being able to operate experimental digital equipment under varied test conditions is certainly one reason that the designers of digital mobile equipment have retained the feature of "plugging into" FM voice equipment.

The prospective user of digital equipment, too, benefits from this "plug in" symbiosis. He is concerned with his particular communication requirement at hand and the two most important questions, (1) "Can digital equipment be of help to me?" and (2) "Which digital system works best in this application?" can be partially answered by letting him try a wide range of digital accessories such as teleprinters, voice digitizer/scramblers, and facsimile copiers in his system. These devices can be tested under his own operational conditions and introduce him to the possibilities of digital communication.

Besides the above operational advantages, the strongest reason for using FM-voice equipment for digital communication is of course the existence of a substantial investment in that equipment. As one manufacturer advertises, "self-liquidating" digital accessories "extend the capabilities" of voice equipment, provide "increased efficiency", yet "in no way interfere with normal voice communication capability". Communications planners can therefore ease into greater use of digital transmissions as they prove helpful in operation.

The use of voice-FM mobile equipment as a common testing ground for both the operational usefulness of digital communications (user's point of view) and the development of technical specifications for digital equipment (equipment designer's point of view) is undoutedly a healthy situation, but the concomitant danger is that users and designers might mistake the good or bad digital characteristics of FM equipment for the true characteristics of the radio channel. The true channel characteristics are from A to A' in Fig. 24 but the digital "add-ons" depend on the equipment characteristics

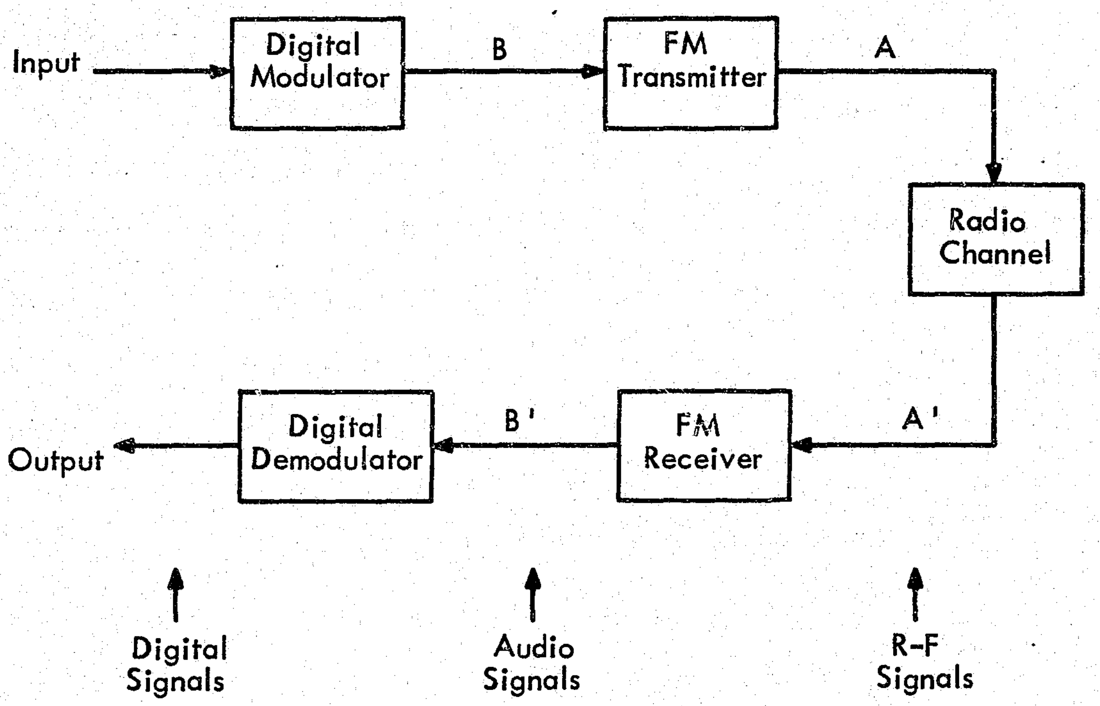


Fig. 24 "Plug-in" Digital Modulator and Demodulator

from B to B' and these secondary characteristics may have compromised the channel from a digital point of view due to the introduction of phase distortion, threshold effects, and noise "clicks" in the FM equipment itself. These topics are discussed below.

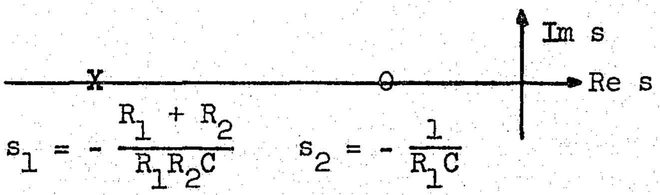
1. Phase distortion

FM equipment is usually designed to have a flat audio amplitude response from 300 to 3,000 Hertz, but the audio phase is deliberately distorted by pre-emphasis and de-emphasis circuitry which improves the audio signal -

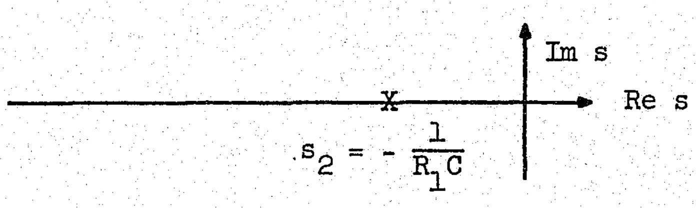
to-noise ratio. Unfortunately, this is a case in which voice and digital design criteria conflict. As shown analytically below and graphically in Fig. 25, digital pulses are sharpened by the pre-emphasis circuit and smeared in a noncomplementary fashion by the de-emphasis circuit. No additional filtering can remove these distorting effects so, in order to obtain better digital characteristics, most digital demodulators pick off the received FM signal at the discriminator output (before the de-emphasis circuit) and some digital modulators even bypass the transmitter pre-emphasis circuit, modulating with the digital signal directly.

The "click" or "anomaly" noise in FM is an impulsive type of noise with strong noise power components at high frequencies, and the anti-noise strategy is to simply boost the audio "highs" at the transmitter, while at the receiver a complementary filter attenuates the "highs" back to their proper level. In this way the audio signal-to-noise ratio is improved. The following frequency-domain analysis shows that the filter characteristics $H_1(s)$ and $H_2(s)$ are complementary over the audio range and do not affect voice quality, while providing considerable attenuation of the channel noise at the receiver:

$$H_1(s) = \frac{R_2\,(1 + R_1Cs)}{R_1 + R_2 + R_1R_2Cs}$$



$$H_2(s) = \frac{1}{1 + R_1Cs}$$



520-418 O - 74 - 5

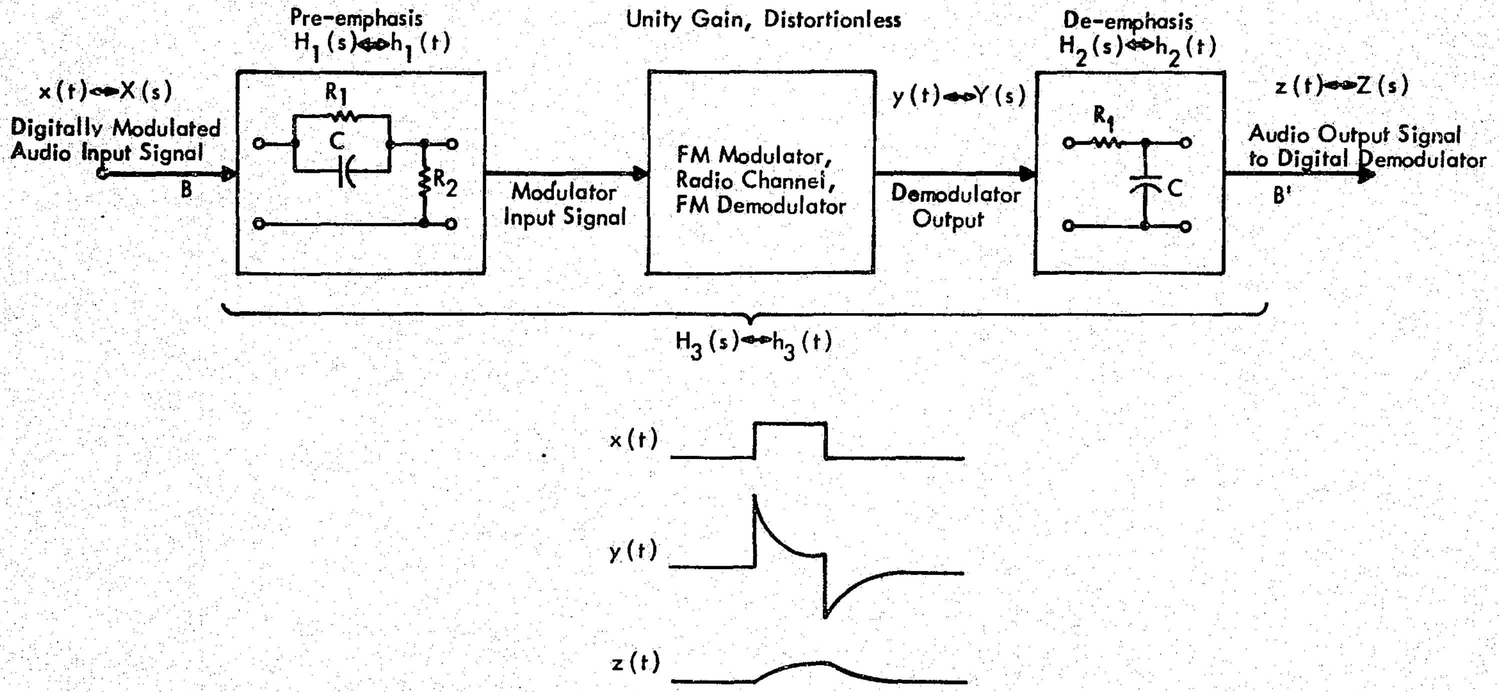


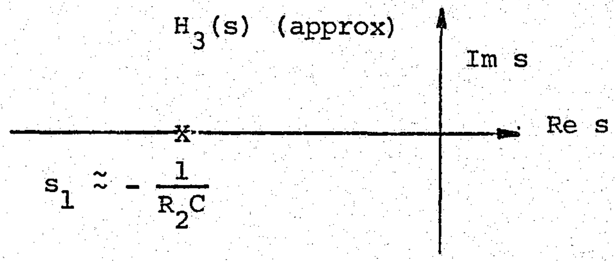
Fig. 25 FM Preemphasis/Deemphasis Circuits and Pulse Response

$$H_3 = H_1(s)H_2(s)$$

$$= \frac{R_2}{R_1+R_2+R_1R_2Cs}$$

$$\cong \frac{R_2}{R_1} \circ \frac{1}{1+R_2Cs}$$

$$R_1 >> R_2$$



typical values:*

$$s_1 \cong -\frac{1}{R_2C} = -11{,}000/\text{sec}$$

$$s_2 = -\frac{1}{R_1C} \cong \frac{1}{15}s_1 = -730/\text{sec}$$

In the time domain, on the other hand, the pre-emphasis/de-emphasis circuits are not exactly complementary, as shown by Fig. 26 and the following time-domain (step response) analysis:

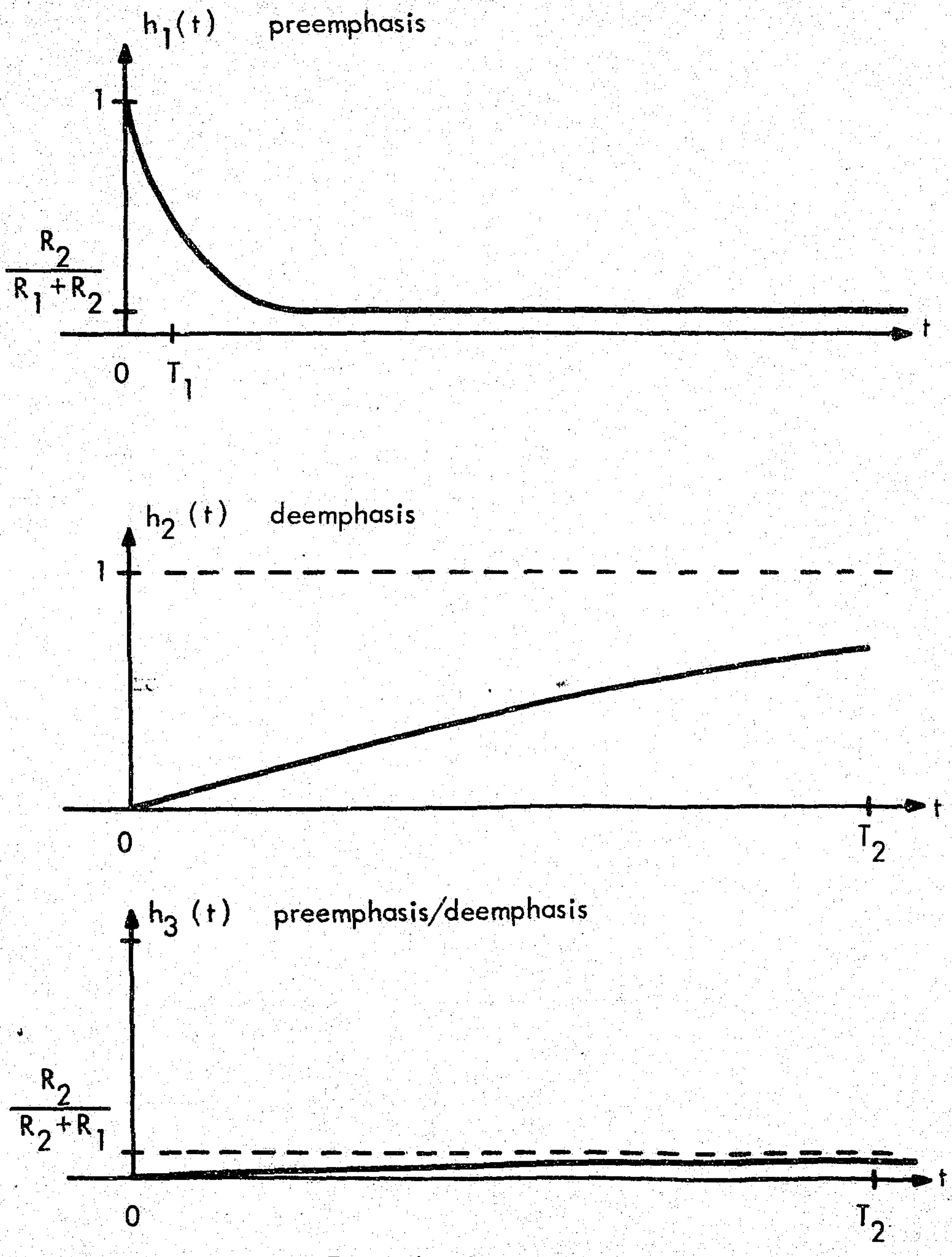
$u_{-1}(t)$ = unit step function

$$h_1(t) = \left[\frac{R_2 + R_1 \exp\{-\frac{R_1R_2}{R_1R_2C}t\}}{R_1 + R_2}\right] u_{-1}(t)$$

$$h_2(t) = \left[1 - \exp\{-\frac{1}{R_1C}t\} \;\; u_{-1}(t)\right]$$

---

*Derived from land mobile maintenance manual: R_2 = 1.62K, C = .056 μf, and M. Schwartz: Information Transmission, Modulation and Noise, p. 305, 1959.



Typical values: $R_1 = 15\,R_2$

$T_1 = 91\ \mu\text{sec}$

$T_2 = 1.36$ msec

Fig. 26 Step Responses of FM Preemphasis/Deemphasis Circuits

$$h_3(t) = h_1(t)*h_2(t)$$

$$= \frac{R_2}{R_1+R_2} \quad 1\text{-exp} - \frac{R_1+R_2}{R_1R_2C}\, t \quad u_{-1}(t)$$

$$\cong \frac{R_2}{R_1} \left[1\text{-exp } (- \frac{1}{R_2C}\, t) \right] u_{-1}(t)$$

$$R_1 >> R_2$$

typical values: $T_1 = 1/s_1 \cong R_2C = 91\mu\text{sec}$

$T_2 = 1/s_2 = R_1C \cong 15\ T_1 = 1.36\ \text{msec}$

These time-domain distortions--especially the "smearing" of the de-emphasis circuit--have a serious consequence for digital transmission. For example, if the digital signal is introduced into the normal audio channel (including the filters), it is only possible to send one bit per six "smearing" time constants T_2 which is approximately one bit per 8.16 msec or 122 bits/second. This compares to the Nyquist rate for a 2700-Hz audio bandwidth of 2W = 5400 bits/sec. The need for "data" jacks which bypass the audio filters is therefore obvious if rates higher than about 100 bits/sec are desired.

2. Threshold effect in FM

The probability of error due to the existence of a threshold in bandwidth-exchange systems such as FM has already been analyzed in Chapter 2. Taking a slightly broader view of the situation, the brief drops of signal below threshold (due, for instance, to Rayleigh-distributed multipath fades) cause actual gaps in the signal output of the receiver. There is only a slight loss of voice information due to these gaps because of the natural structure of language which permits the listener to "fill in" the short gaps mentally. Digital receivers are not so smart; when a few bits are missed during a fade they are gone forever. In fairness, some redundancy can be deliberately introduced by coding (an idea to which we shall return in Chapter 4)but the point is: brief fades below FM threshold are only irritating in voice transmission, but cause special digital difficulty because they cause bits to be missed.

3. Click noise in FM

As has been discussed above, click noise in FM is impulsive, and from our previous analysis of impulsive noise, we might expect it to cause digital errors. The characteristics of click noise can be derived from rather intuitive geometric arguments[32] but for our purposes it is sufficient to note that these clicks remain present even at high signal-to-noise ratios, becoming less frequent, but if anything, more sharply peaked. We then realize that, by electing to digitally modulate FM voice equipment (digital submodulation), we are left with the essential existence of impulsive "click" noise above threshold. For the near future, these digital disadvantages of FM equipment (click noise, complete loss of signal below threshold, and phase distortion) are unimportant when compared with the operational advantages of "plug in" digital equipment. It seems probable however that when digital mobile radio usage has matured to the point where it no longer need be handled on an "add-on" basis, FM submodulation will be replaced by some form of direct modulation for high-speed digital transmission.

CHAPTER 4

DESIGN ISSUES IN DIGITAL SYSTEMS

The previous two chapters have outlined first the "facts of life" concerning the basic mobile radio channel as it de facto exists today and its effects on digital transmission, and second, the external constraints (sunk investment in existing equipment, spectrum management issues) which affect what might be done about the channel to improve the speed and efficiency of digital transmission. This chapter discusses a number of technical issues that must be considered in the design of a digital mobile communications system.

The first issue, discussed in Section A, concerns the problem of maintaining communications discipline in a digital query-response system. Humans operating on voice channels can easily resolve the conflict problem on shared channels, but machines are not that adaptable--the link discipline must be carefully thought out ahead of time and designed in. Section A discusses two general strategies and the tradeoffs between them in regard to response time as a function of the number of mobile units.

The next two sections, B and C, describe two techniques for reducing the error rate of a digital channel and thereby improving its efficiency--diversity transmission and message coding. These may be used separately or in combination, and again, there are many tradeoffs to be made in designing a system for a particular application. One form of diversity, use of two or more frequencies, appears to be the only practical one for portables but has received almost no attention in the land-mobile literature, probably because of the spectrum congestion that prevails. With the recent augmentation of the land-mobile spectrum, it should perhaps be given consideration if digital communication with portables is envisaged.

Finally, Section D presents a simplified comparison of digital error rates for two forms of channel modulation--direct FSK and FSK submodulation of FM--and points up the tradeoffs to be made between channel rate and channel error rate in trying to optimize channel efficiency, measured in terms of the rate of <u>correct</u> messages communicated.

One additional systems issue is discussed in Appendix A. This is the question of the reverse problem of transmitting a digitized analog signal, particularly voice, over a channel designed and optimized for digital data. It is shown that about 30,000 bits per second with a binary error probability of 10^{-3} would be required to achieve acceptable voice transmission with an audio SNR of 30 dB.

A. Mobile Interrogation

In communication between fixed and mobile units it is usually not a procedural problem to "talk out" from the base station. In voice systems the base communicator (dispatcher) often has his own channel and he maintains "talk in" discipline by directing individual mobiles to reply as directed. Problems arise only when two or more mobiles try to initiate messages at the same time so that none of the messages gets through the mutual interference.

A similar organizational pattern is found in most digital mobile radio systems. Due to the "times N" factor discussed in Chapter 3, most of the organizational authority is concentrated at the base station to transmit in sequence to designated mobiles and, as much as possible, direct the mobile units to reply in a specified sequence.

1. Mobile polling

The role of the base station controller as "puppet-master", controlling every transmission from the base station as well as from the mobile units, can easily be expanded to allow for base station control of mobile-originated messages. In such a "polled" system each vehicle is usually assigned its own time slot in which to send a code indicating whether or not it wishes to originate a digital message. Once the intent to send a message has been registered, the base station directs the mobile to send its message at a designated time. Polling has the advantage of conceptual simplicity and it is also impossible for one mobile to interfere with another because none of the mobiles "speaks" until it has been "spoken to" by the base station (unless errors in control messages cause more than one mobile to transmit simultaneously).

More exactly, consider a fleet of N mobile units in which each mobile originates a message every M seconds on the average (M is the minimum average time between message originations for any one of the mobiles). Suppose the base station polls each vehicle every NT seconds so that N time slots, one for each mobile, are available every NT seconds; that is, the time slot for any one mobile is available every NT seconds. In order for the time slot occurrences to keep up with the most rapid message origination rate on the average it is necessary that

$$T \leq M/N \tag{1}$$

where N = number of mobiles
NT = time between a particular vehicle's time slots
M = minimum average time between message originations for anye one mobile.

Furthermore, since each mobile may originate a message with uniform probability over the interval NT the average delay time, D, for each mobile will be

$$D = \frac{1}{2} NT \tag{2}$$

where D = average time delay between a mobile's message origination and its next time slot.

2. Random origination

Before examining a different interrogation process (random input) we should pause and consider in more detail the statistics of mobile message origination. We will use the Poisson distribution to describe the time intervals t_o between message originations at a mobile.

$$\text{Prob } (t_o \leq T) = 1 - \exp(-T/M')$$

where M' is the average time between message originations for all mobiles. Note that

$$\text{Prob } (t_o \leq T) \leq T/M' \tag{3}$$

which bounds the probability that a message is originated at a mobile during the interval T.

Random input interrogation substitutes unaddressed time slots for the addressed time slots of the polling system. In a random input system a mobile can indicate that it has originated a message during any time slot and the only danger is that two or more mobiles may try to transmit during the same time slot, interfering with each other's transmissions. If such interference occurs, the mobiles must have some "randomizing" factor built in to prevent them all from again trying to transmit during the very next time slot (when they would again mutually interfere), or the following time slot, etc.

Barring such a hangup, we are concerned with the probability that two or more mobiles may transmit during a particular time slot and interfere.

Transmissions	Interference?	Probability
no mobiles	no	$P(0) = (1 - P)^N$
one mobile	no	$P(1) = NP\ (1 - P)^{N-1}$
two mobiles	yes	$P(2) = \binom{N}{2}\ P^2\ (1 - P)^{N-2}$
⋮	⋮	⋮
N mobiles	yes	$P(N) = P^N$

The probability, P, that any one mobile will originate a message during the period T between time slots is less than T/M' from Eq. 3. By making T sufficiently short we can adjust P so that P_i, the probability of any interference is approximately:

$$P_i = \sum_{j=2}^{N} P(j) = \sum_{j=2}^{N} \binom{N}{j} P^j (1-P)^{N-j}$$

$$\overset{\sim}{=} \frac{N(N-1)}{2} \left(\frac{T}{M'}\right)^2 \qquad \text{for } T << M'$$

P_i can be made less than ε only if

$$\frac{N(N - 1)}{2} \left(\frac{T}{M'}\right)^2 \leq \varepsilon$$

which requires that

$$T \leq M'\sqrt{\frac{2\varepsilon}{N(N-1)}} \overset{\sim}{<} \frac{M'}{N} \sqrt{2\varepsilon} \qquad (4)$$

where ε is the maximum probability of interference.

This required time interval T between time slots leads to an average delay time between message origination and interrogation because (1) it is still necessary to wait until the first time slot just as for polling but also (2) it is possible (probability $\leq \varepsilon$) that another mobile might interfere and force a wait of T seconds for another time slot, etc., as shown in Fig. 27.

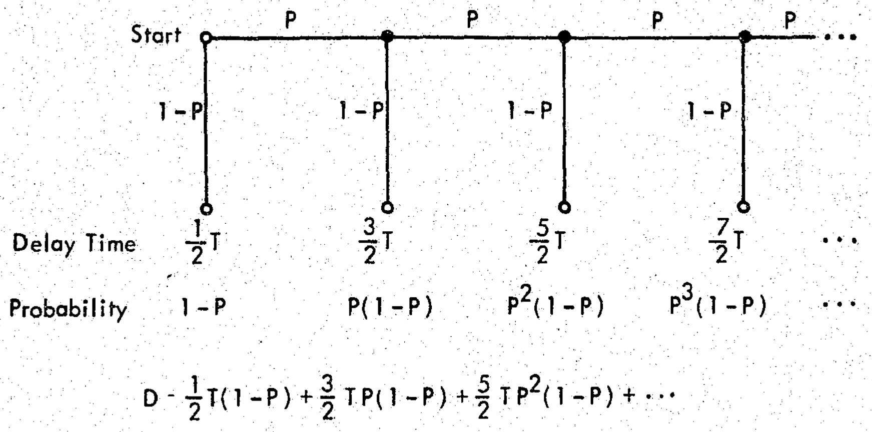


Fig. 27 Queue Delay for Random-Input Interrogation with Probability of Interference P

From Fig. 27 we can calculate the average time delay D.

$$D = \sum \text{(time delay) (probability of that delay)}$$

$$= \frac{1}{2} T(1-\varepsilon) + \frac{3}{2} T\varepsilon(1-\varepsilon) + \frac{5}{2} T\varepsilon^2 (1-\varepsilon) + \ldots$$

$$= \frac{1}{2} T + \varepsilon T + \varepsilon^2 T + \varepsilon^3 T + \ldots$$

$$= \frac{1}{2} T + T(\frac{\varepsilon}{1-\varepsilon}) \qquad (5)$$

3. <u>Comparison of polling and random input</u>

Using Eqs. 1 through 5, we can compare polling and random input interrogation techniques as shown in Table 3 for the same value of NT (i.e., for the same interrogation "overhead") and for equal message origination rates (M = M'). In the polling system the time slots are addressed, for random input they are unaddressed.

Table 3

Parameters for Polling and Random Input Systems

Parameter	Polling	Random Input
T	$\frac{M}{N}$	$\frac{M'}{N} \sqrt{2\varepsilon}$
N	$\frac{M}{T}$	$\frac{M'}{T} \sqrt{2\varepsilon}$
D	$\frac{1}{2}$ NT	$T(\frac{1}{2} + \frac{\varepsilon}{1-\varepsilon})$

T = maximum period between any two time slots

M = minimum average time between message originations for any one mobile (polling)

M' = ensemble average time between message originations for all mobiles (random input)

ε = maximum probability of interference (random input)

D = average time delay between a mobile's message origination and its next available time slot at a slot rate of 1/T

N = maximum number of mobile units

Table 3 shows that allowing the interrogation time slots to remain unaddressed (and therefore allowing for a certain probability of interference) reduces the maximum number of mobiles. This happens because the time slot occurrences must be more frequent in order to reduce the probability of interference. So, for a fixed time slot spacing, the maximum number of mobiles is reduced. Fortunately, the reduction in mobile capacity is not drastic: for a maximum interference probability of 10^{-2} (i.e., only one message out of a hundred does not get through on the first try) the maximum number of mobiles is reduced by a factor of $\sqrt{.02} = .141$, or to about 1/7 of the polling capacity. For digital mobile radio systems in which maximum mobile capacity is very important or in which the mobiles originate messages at a steady rate (such as vehicle location systems), the polling technique might be preferred.

On the other hand, the random-input system has a much shorter average time delay, especially for large numbers of mobiles, and for digital mobile radio systems in which response time is important (such as public service systems), the random input technique might be preferred. Random input and polling techniques are compared in Table 4 for two hypothetical mobile radio systems having 20 and 200 mobiles for $M = M' = 5$ minutes and $\varepsilon = 10^{-2}$. In Table 4, two polling columns are shown. The first one has the slot time calculated as per the polling column of Table 3, which produces rather slow polling rates and long delays. The second one has the slot times set the same as for random input so that polling and random input can be more readily compared on an equal slot-time basis. It is seen that under the assumed conditions, the random input enjoys a 20:1 improvement in average delay D for 20 mobiles, and a 200:1 improvement for 200 mobiles.

Table 4

Random Input and Polling Techniques for
Two Hypothetical Mobile Radio Systems

M = M' = 5 minutes = 300 seconds

$\varepsilon = 10^{-2}$

T = maximum period between any two time slots

D = average time delay between a mobile's message origination and its next available time slot

N = 20	Polling (1)	Polling (2)	Random Input
T	15 sec	2.1 sec	2.1 sec
D	2.5 min	21 sec	1.05 sec

N = 200	Polling		Random Input
T	1.5 sec	0.21 sec	0.21 sec
D	2.5 min	21 sec	0.10 sec

B. Diversity Techniques

In Chapter 2 we have seen that multipath propagation causes amplitude fading of the signal, and that this fading can be described analytically by the Rayleigh probability density function. We have also seen that there is a significant probability that a Rayleigh-distributed signal amplitude might fade to a very low level resulting in a sharp increase in the probability of digital errors.

Assuming digital errors are only due to Rayleigh-distributed signal fades, one way to improve the digital error probability would be to reduce the probability of signal fades below a given level by the "brute force" approach--simply increase the transmitter power until the probability of digital error is acceptably small. This strategy may seem especially attractive considering the low additional cost of transmitter power, but for the Rayleigh probability distribution, every factor of ten reduction in the probability of fade and, therefore, every decade reduction in digital error probability requires a ten-fold (10 dB)increase in signal power. This means, for example, that to reduce an error rate from 10^{-3} (for 10-watt base and mobile transmitters) to 10^{-6} by increasing the transmitter power would require transmitter powers of 10 Kw for the base and mobiles! Such very high powers are obviously impractical, not only from a cost viewpoint, but on the basis of geographic frequency reuse.

1. Theory of diversity

Diversity transmission is often proposed as an alternate solution to the problem of digital errors in mobile radio communication due to multipath fading. The idea behind diversity communication is to transmit the same signal over N statistically independent Rayleigh-fading channels and to rely on the fact that all N channels will be faded at once with very small probability. Stated more precisely, the probability density for the signal power of a Rayleigh-fading signal is largest for small values of signal power as shown in Fig. 28 and derived analytically below. As the number of diversity channels, N, increases, the probability density of the signal power becomes sharply peaked (i.e., signal fades become less probable) and the exact distribution tends towards a Gaussian distribution. In the limit of infinite N, the probability density becomes impulsive and the signal is no longer fading.

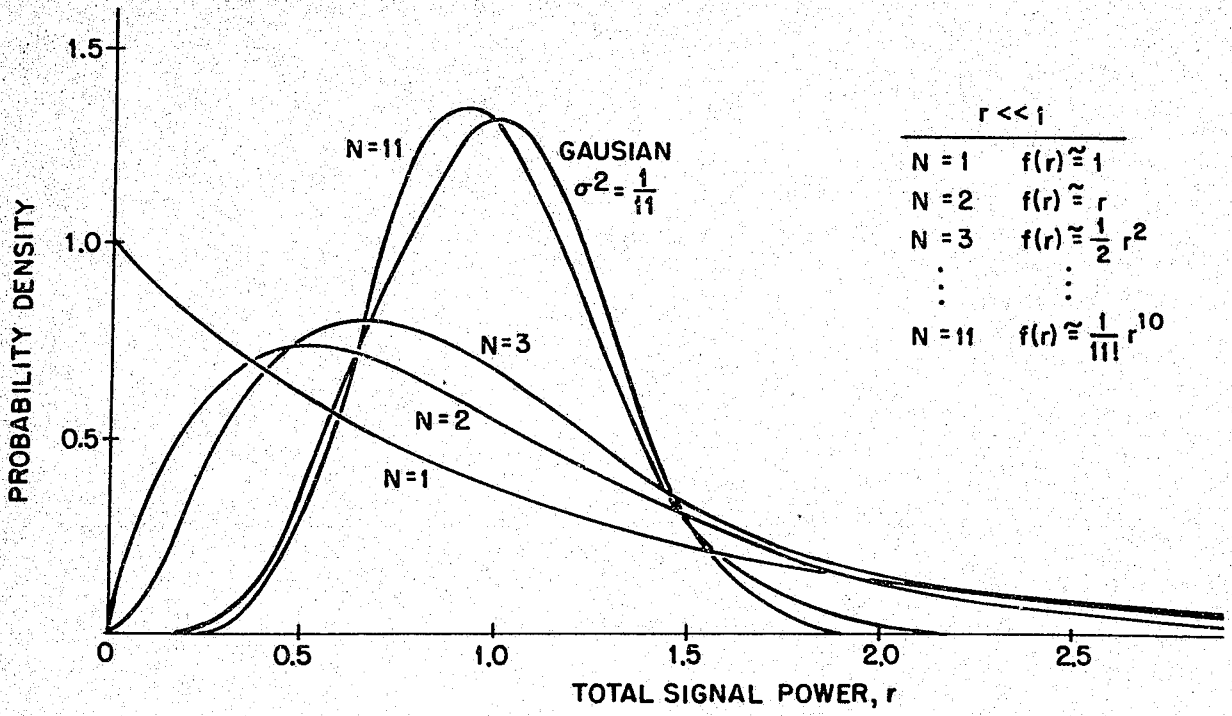


Fig. 28 Power Probability Densities for N-Branch Summation Diversity

The probability density function for the power of a Rayleigh-fading signal is

$$f_1(r) = \frac{1}{a} \exp\left(-\frac{r}{a}\right) \qquad \begin{array}{l} \text{mean} = a \\ \text{variance} = a^2 \end{array}$$

and its moment-generating function (Laplace transform) is

$$F_1(s) = L[f_1(r)] = \frac{1}{1 + as} .$$

The moment-generating function for the total signal power of N independent channels (i.e., the sum of N independent identically-distributed random variables)is

$$F_N(s) = [F_1(s)]^N = \frac{1}{(1 + as)^N}$$

so the probability density function for the power of an N-branch diversity signal is

$$f_N(r) = L^{-1}[F_N(s)] = \frac{r^{N-1}}{a^N(N-1)!} \exp\left(-\frac{r}{a}\right) \qquad \begin{array}{l} \text{mean} = aN \\ \text{variance} = a^2N \end{array}$$

Any N independently fading channels would form a legitimate diversity arrangement and some of the candidates are time, polarization, space, and frequency separation of signals. These will be discussed in Section 2 below.

In using any one of these diversity methods, the problem always arises: what is the best way to combine N independent diversity signals? Brennan[37] has shown that, for linear modulations, a proportionately weighted sum yields the highest signal-to-noise ratio while a simple summation is only slightly inferior. Figure 29 shows Brennan's results for N = 2 (left graph) and N = 4 (right graph). For non-linear modulations (such as FM and digital modulations), selection diversity ("select the signal with the highest signal-to-noise ratio at each instant of time") is superior to summation although the optimal combination rule is unknown.

Using the power probability densities which led to Fig. 28, we can verify the similar results of selection and summation on N-branch diversity.

Selection: $P = \text{Prob}(r \leq r_o) = \text{Prob}(\text{all N signal powers} \leq r_o)$

$$= \left[\int_o^{r_o} f_1(r)\,dr\right]^N = \left[1 - \exp\left(-\frac{r_o}{a}\right)\right] \cong \left[\frac{r_o}{a}\right]^N$$

Summation: $P = \text{Prob}(r \leq r_o) = \int_o^{r_o} f_N(r)\,dr \cong \frac{1}{N}\left[\frac{r_o}{a}\right]^N$

Since these two methods are so similar for small N, and considering the ease of implementation for selection diversity and the superiority of selection diversity for non-linear modulations, selection seems to be preferable for

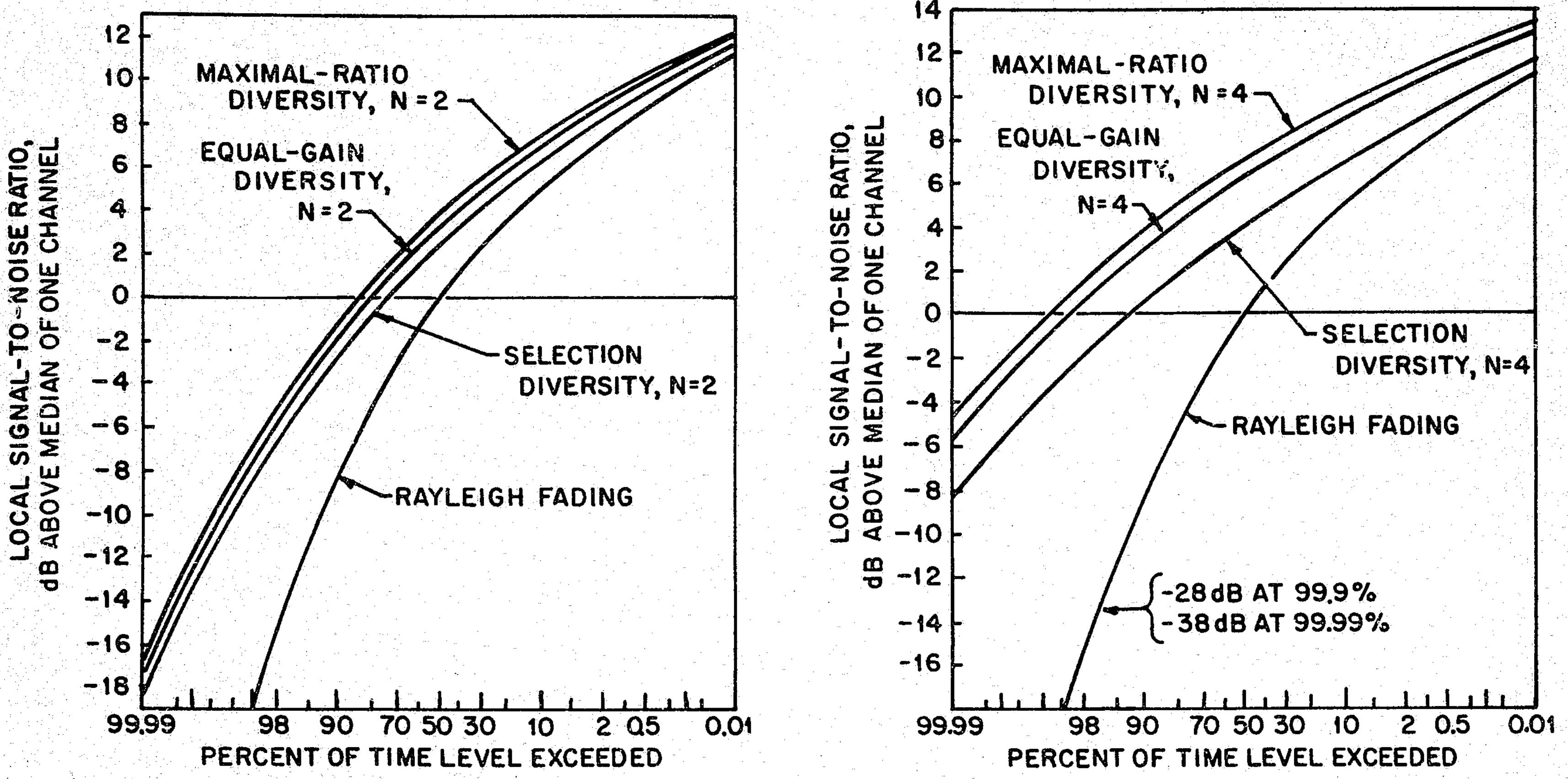


Fig. 29 Amplitude Distributions for Maximal-Ratio, Summation, and Selection Diversity[37]

digital mobile radio diversity communication.

2. Which type of diversity?

Time diversity can be ruled out in mobile radio communication by the fact that a mobile may stop momentarily in a signal null. If the multipath geometry remains fixed, all the time-repeated signals will be identically faded and no diversity is achieved.

Polarization diversity has received some experimental attention and it seems that the electric and magnetic components of the electromagnetic signal fade independently enough that effective dual diversity is possible.[34] The disadvantage is that two separate receivers and a complicated antenna (a so-called "energy density" antenna) are required for all mobiles.

Space diversity has also received considerable theoretical and experimental attention. Lee has shown theoretically[35] that for receiving antenna spacings greater than 0.2 wavelength the mutual coupling among antennas is unimportant and that the received signal amplitudes may be mutually independent. Experimental studies[36] of space diversity reception have shown that antenna spacings as close as 3/4 to 5/4 wavelength yield effective diversity reception (see Fig. 30). Although the receiving antennas may be simple whips, N antennas and N separate receivers are required for each mobile for N-branch diversity. Furthermore, the mobile must be large enough physically that N antennas can be spaced up to 5/4 wavelength apart, a factor which rules out space diversity reception for hand-held portables at least.

The last diversity technique, frequency diversity, has received insufficient experimental attention. In Chapter 2 the required frequency separation for independently fading signals was stated in terms of the maximum multipath time delays and it is always possible to obtain N independent signals in that fashion. Frequency diversity does require an N-channel receiver but only one antenna. It therefore appears to be the only practical diversity arrangement for portable units. It therefore warrants serious consideration although it does require N times as much spectrum as the other diversity methods.

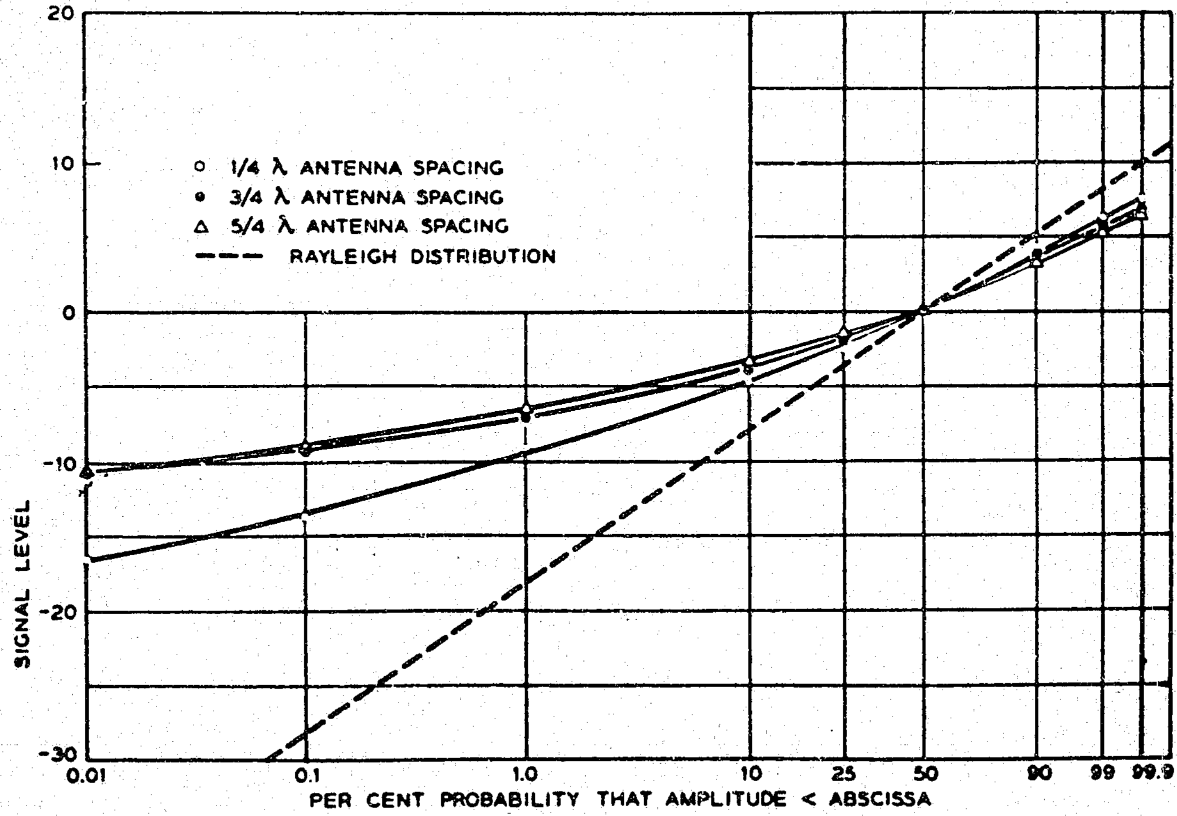


Fig. 30 Experimental Signal Amplitude Distributions for 4-branch Summation Space Diversity with Different Antenna Spacings.[36]

Before leaving the subject of diversity communication, it is important to note that all of the improvement credited to diversity transmission is due to the assumption that digital communication is solely limited by Rayleigh signal fading. For digital mobile radio communication it is not at all clear whether experimentally observed digital errors are due to signal fading which is amenable to diversity improvement or to ambient noise which is immune to diversity improvement. This determination must be made before great hope is placed on any reduction of digital error rates in mobile radio communication due to diversity techniques alone.

C. Coding

In digital mobile radio communication our major concern is data integrity. We would like to be sure that the information which has been transmitted is received exactly as sent because, more often than not, it is better to completely miss a message than to accept one which contains an error. "No data is better than wrong data".

Digital coding techniques can provide just this kind of assurance. Generally speaking, digital codes are of two types--error-detecting codes and error-correcting codes. The purpose of an error-detecting code is simply to flag a message that is found to have been received with one or more bit errors so that a retransmission can be requested. An error-correcting code will both detect and automatically correct a given number of errors, and act as an error-detecting code for some number of errors beyond that which it is able to correct. Both code classes require message redundancy (extra information bits derived from the message contents and added to it for transmission)and this "overhead" reduces net message rate over a channel of a given bit rate--more so for error-correcting codes because of their greater redundancy.

It seems clear that a mobile digital communications system cannot operate without some form of error detection, and at least some level of redundancy must therefore be accepted. Note however that a message with even a single error must usually be repeated, effectively halving channel rate for that message. The question is then whether the added redundancy of an error-correcting code that will save many such message repeats results in a net improvement in correct message rate over the channel. The greater hardware complexity of error-correcting coders and decoders must also be considered.

In this section on coding we will discuss three broad classes of codes which can introduce error detecting or error correcting "grammar" into binary sequences: parity check, cyclic, and convolutional codes. They will be presented superficially, but sample circuits have been included for definiteness and to demonstrate that all three classes of codes have modest circuit requirements. The material in this section borrows very heavily from Information Theory and Reliable Communication by Robert Gallager (1968)[39] and from Principles of Communication Engineering by John Wozencraft and Irwin Jacobs (1967).[32] The following quotation is of interest:

> "Perhaps the most important point about coding techniques is that they are practical in a variety of communication systems. This point can be easily missed because of a strong human tendency to confuse the familiar with the practical. This point is also sometimes missed because of the large number of digital operations performed in a coder and decoder. Such operations tend to be highly reliable and easy to implement, even though difficult to understand."
>
> ---- Gallager, p. 305

1. Parity check codes

Parity check codes are the simplest of the block error-control codes, and the Hamming parity check codes with minimum-distance* two or three are especially popular. For example, a minimum-distance-three Hamming code has a block length of seven digits and there are four information digits. The coding/decoding circuitry for this (7,4) parity check code is shown in Fig. 31.

The minimum-distance-three Hamming codes all have N-L check digits such that the block length, N, and the number of information digits, L, satisfy[38]

$$N = 2^{N-L} - 1 \tag{6}$$

and each such minimum-distance-three code is able to

detect up to 2 errors or
detect and correct 1 error

in the block of N digits. The ratio of check digits to information digits (the code's fractional redundancy) is a measure of how severely the net data rate is reduced by the additional coded check bits. From Eq. 6 the redundancy is

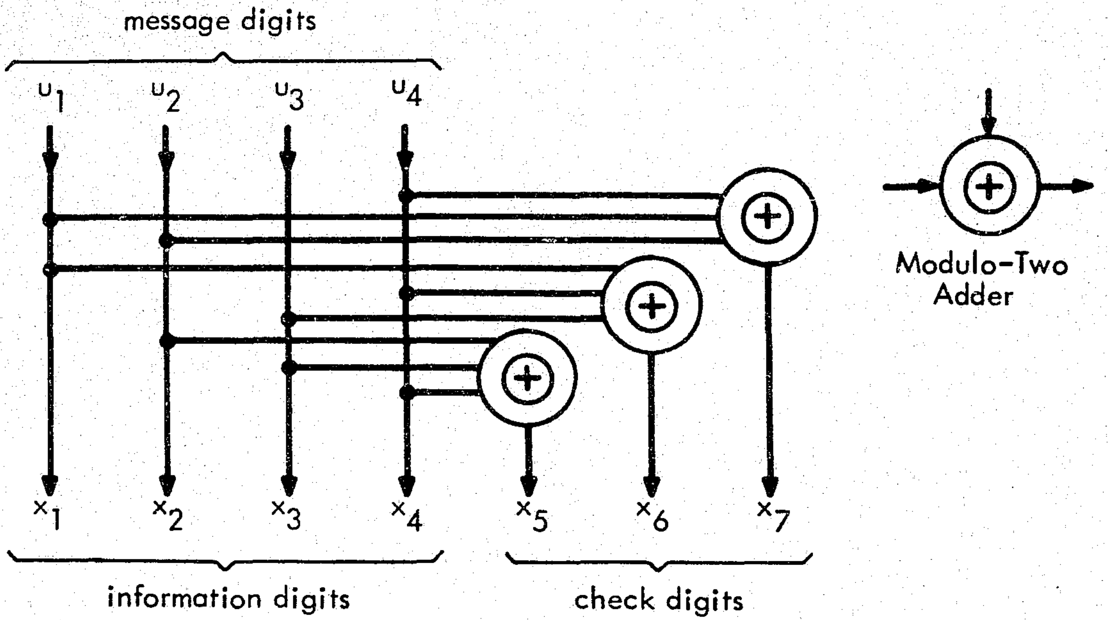
$$\frac{N - L}{L} = \frac{\log_2 (N+1)}{L} = \frac{\log_2 N}{L} \text{ for } N >> 1.$$

Because some (but not all) sequences of more than two errors can be detected, the probability of an undetected error** in a block of N digits is less than the probability that more than two errors may occur in the block.

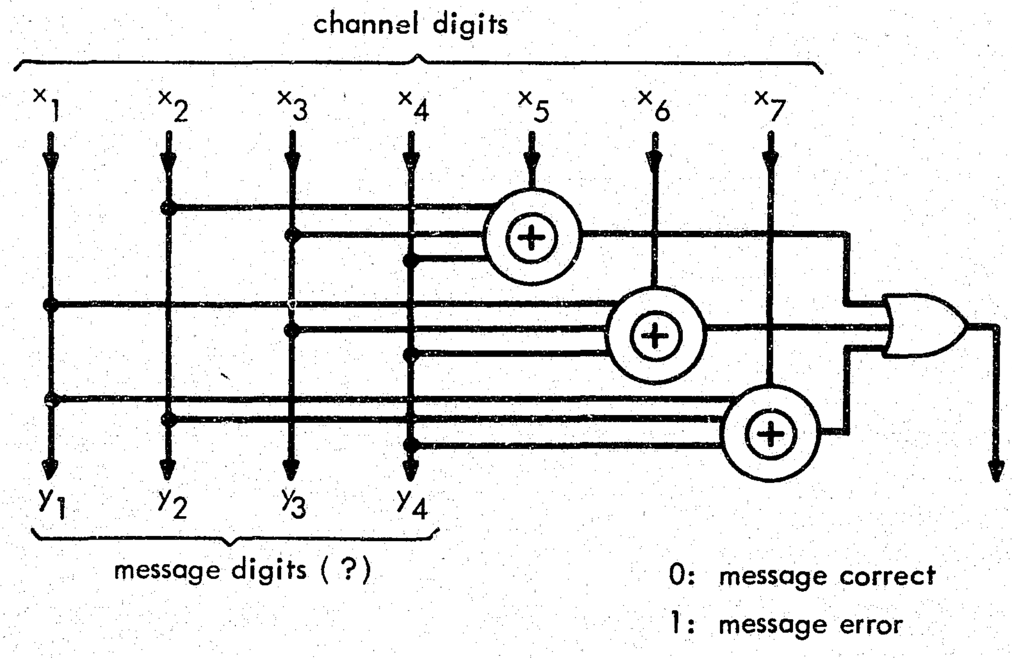
---

*"Minimum distance" is the smallest number of binary places in which two coded sequences must differ and it is a good measure of the error control power of a block code.

**Calculations of undetected error probabilities in this section presume independent error occurrences.



Parity Check Encoder



Parity Check Decoder

Fig. 31 Parity Check Coding[38]

$$
\begin{aligned}
\text{Prob (undetected error)} &\leq \text{Prob (more than 2 errors in a block)} \\
&\leq 1 - [\, P \text{ (no errors)} + P(2 \text{ errors})] \\
&\leq \frac{N(N-1)(N-2)}{6} P^3 + \text{higher order terms} \\
&\gtrsim \frac{N^3 P^3}{6} \quad \text{for } N >> 1 \text{ and } NP << 1
\end{aligned}
$$

2. Cyclic codes

Cyclic codes are another class of block codes which have gained popularity due to their very simple circuit realizations and powerful error detecting abilities. Figure 32 shows the shift register encoder/decoder circuit for a cyclic code of block length 15 (11 information digits and 4 check digits) whose minimum distance is also three. In operation, the 11 information digits are clocked into the encoder one at a time and the shift register is then clocked 4 more times to generate the 15-digit code word. All the shift registers are set to zero and the process is repeated for the next message. Decoder operation is similar. Each 15-digit code word is clocked through the shift register to obtain 11 information digits and 4 check digits. The information digits are accepted as correct only if the check digits are zeros. If any one of the check digits is non-zero, an error is presumed to have occurred and the entire message is rejected.

For the general class of binary cyclic block codes, the block length, N, must satisfy[39]

$$N = 2^m - 1 \tag{7}$$

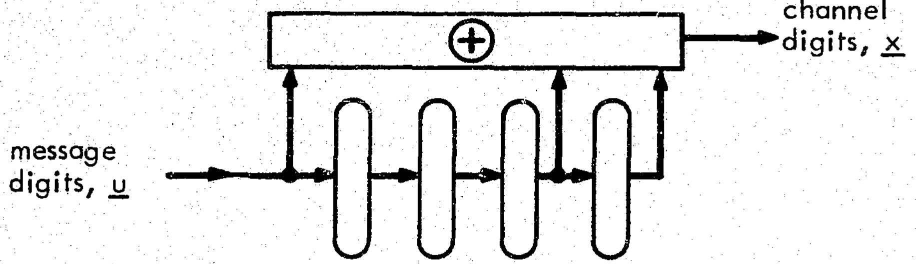
for an arbitrary $m \geq 1$ and the number of check digits, N-L, is

$$N - L = d - 1 \quad (d \text{ odd}) \tag{8}$$

where d is the minimum distance of the code. In other words, these codes can

detect up to d-1 errors or
detect and correct up to $\frac{1}{2}$ (d-1) errors

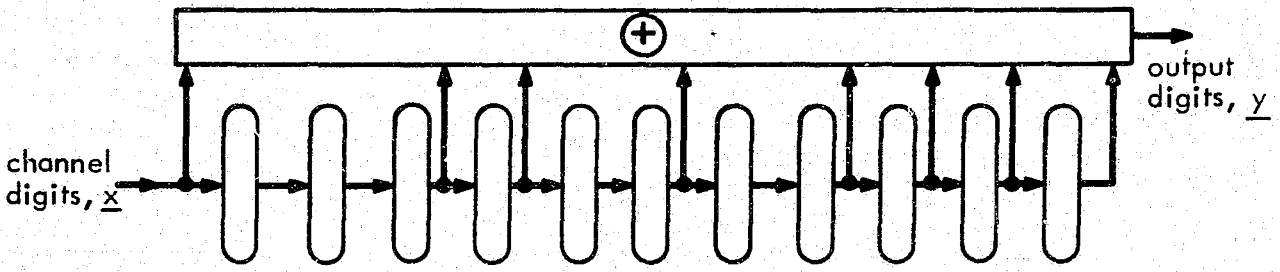
Cyclic Encoder



$\underline{u}$: 1 0 1 0 1 0 1 0 1 0 1

$\underline{x}$: 1 0 1 1 0 1 0 1 0 1 0 1 1 1 1

Cyclic Decoder



$\underline{x}$: 1 0 1 1 0 1 0 1 0 1 0 1 1 1 1

$$\underline{y}:\ \underbrace{1\ 0\ 1\ 0\ 1\ 0\ 1\ 0\ 1\ 0\ 1}_{\text{information digits}}\ \underbrace{0\ 0\ 0\ 0}_{\text{check digits}}$$

Fig. 32 Cyclic Coding[39]

in a block of N digits. The fractional redundancy from Eqs. 7 and 8 is

$$\frac{N - L}{L} = \frac{d - 1}{L} = \frac{d - 1}{2^m - d}$$

Note that the number of check digits is arbitrary. Any number of check digits can be intentionally added to a message sequence in order to reduce the probability of an undetected error which could not be done with a parity check code. The probability of an undetected block error can be adjusted (by varying d) to be

$$P \text{ (undetected block error)} = 2^{-(N - L)} = 2^{1 - d}$$

3. Convolutional codes

Convolutional codes are very different from parity check and cyclic codes because convolutional codes are non-block codes. They are attractive because they also have simple circuit realizations and strong error-correction abilities and are therefore especially appropriate for digital mobile radio communication.

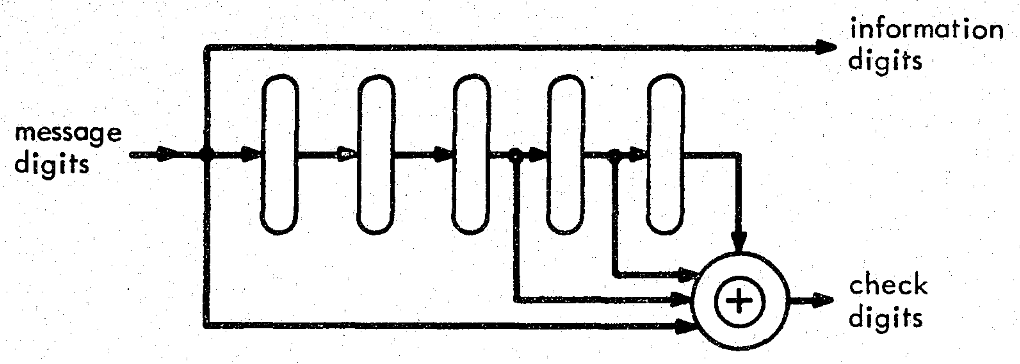
The specific convolutional encoder/decoder of Fig. 33 has been extensively analyzed by Gallager[39] (pp. 258-261) and it demonstrates several general characteristics of a convolutional code.

(1) The convolutional coder/decoder does not require block structure or block synchronization. It operates on data "as it comes".

(2) It efficiently corrects errors with short shift register circuits (here any combination of two or fewer errors among ten or more channel digits will be corrected).

(3) More check digits are transmitted than would have been transmitted for an error detecting code (here there is one check digit per information digit, a fractional redundancy of 1).

Convolutional Encoder



Convolutional Decoder

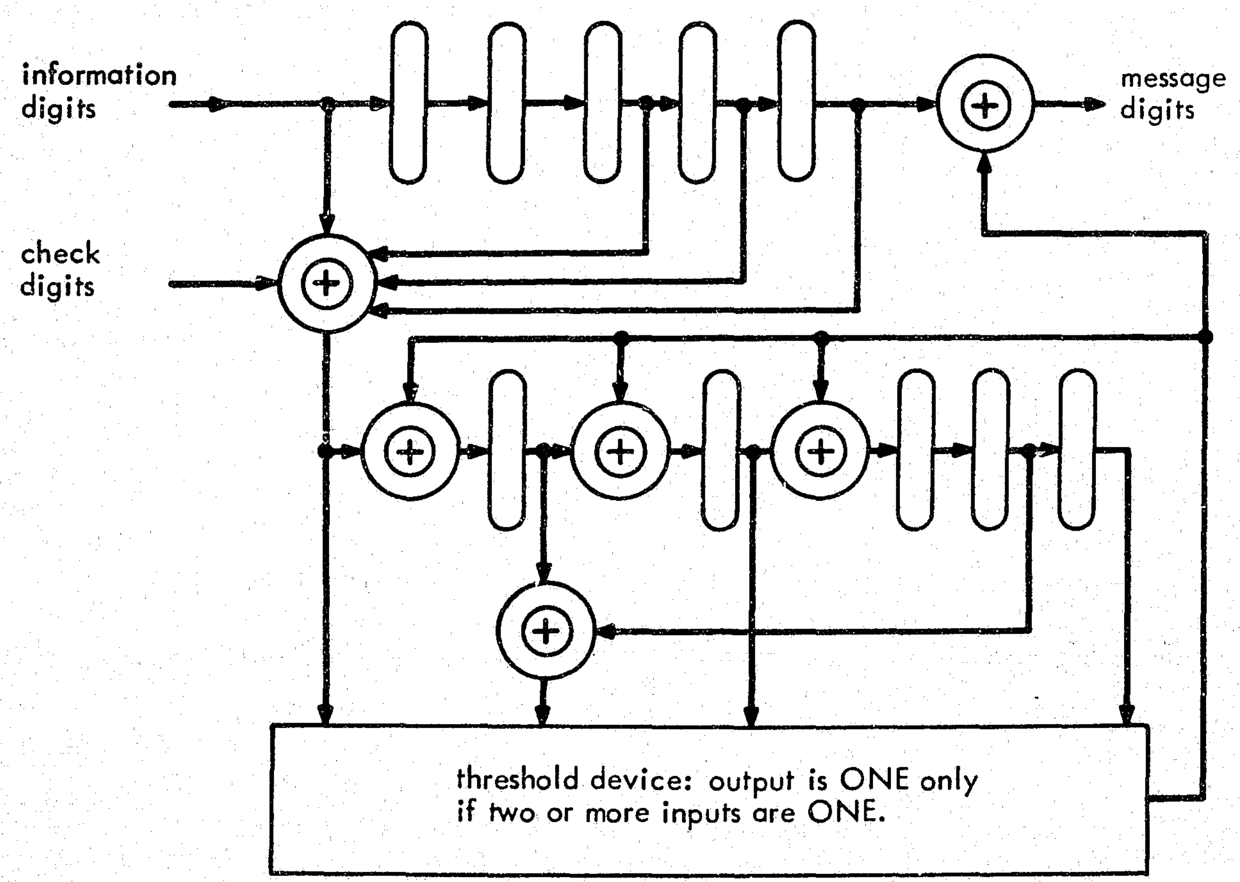


Fig. 33 Convolutional Coding[39]

(4) The convolutional error correction circuitry is very simple--simpler than either parity check or cyclic correction circuits.

4. A suggested two-stage coder/decoder

In order to apply these simple, powerful codes to the mobile radio channel we should first isolate those channel characteristics which will be important in error control. Firstly and most importantly, the channel is a two-way channel over which ARQ (acknowledge/request repeat) techniques can be used. Of course, we might include some error correction to improve efficiency, but we need not rely on error correction alone.

> "The need for a two-way system appears to be unavoidable if communication that is both accurate and efficient is to be maintained over actual communication channels. The parameters of most channels are time-variant, so that their reliability functions fluctuate. A system without feedback must be designed to operate reliably at a data rate commensurate with the worst channel condition, which is inconsistent with efficiency when conditions are good."
>
> -- Wozencraft and Jacobs,[32] p. 456.

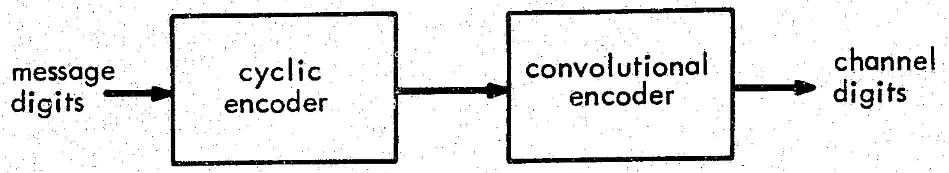
The second important channel characteristic is its model for digital error occurrences. From physical considerations we have identified two quite different types of error patterns in mobile radio communication.

(1) Long series of random errors. These correspond to signal loss due, perhaps, to shadowing or multipath fading. Either kind of signal fade would result in such a long string of errors that an error correction circuit would be very difficult to construct and ARQ would be used instead.

(2) Isolated, independently occurring errors for which convolutional error correction methods are very effective.

In fact, considering the simplicity of digital error control circuitry, a two-stage error control system such as that in Fig. 34 could be recommended. At the decoder, isolated errors are corrected by the first-stage convolutional

Two Stage Encoder



Two Stage Decoder

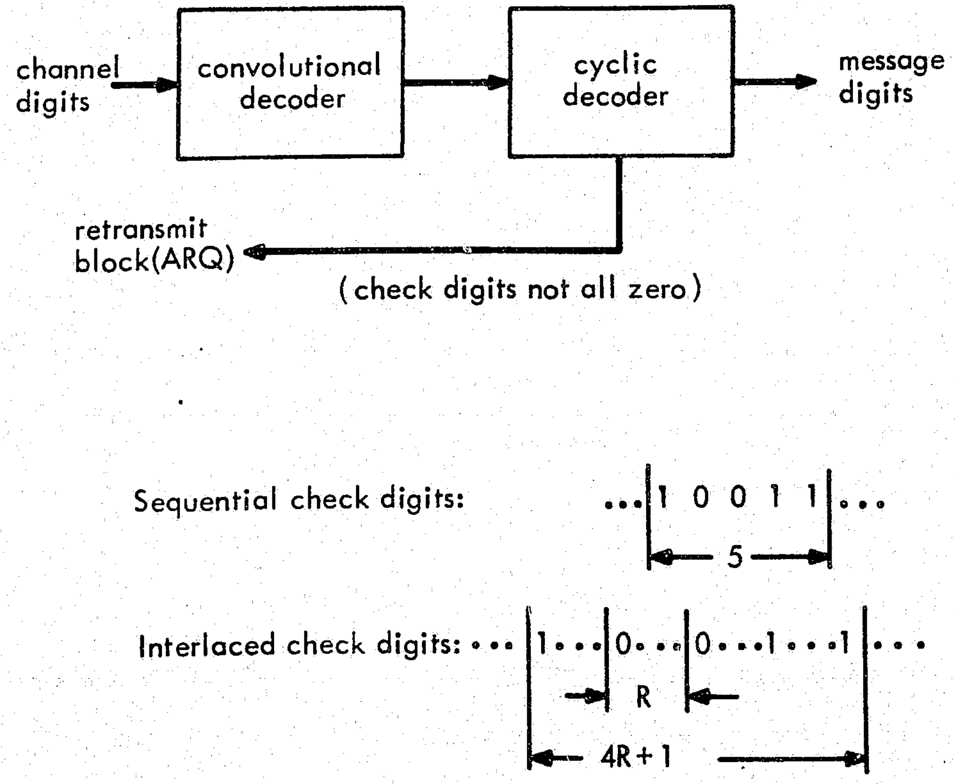


Fig. 34 Two-Stage Coding

decoder and do not require retransmission of a large block of data in order to recover a few missed digits. Cyclic error checking at the second stage serves a double purpose: it asks for retransmission of data blocks (ARQ) which contained a greater density of errors than could be corrected in the first stage and it verifies the accuracy of the received information to whatever confidence level has been specified.

It is interesting to note further in Fig. 34 that the convolutional decoder need not process sequential check digits. If the one-bit shift registers of the convolutional coder/decoder of Fig. 33 were replaced by R-bit shift registers, the decoding operation would proceed as before except that the error correction of a digit would be based not on the values of the last five check digits but on the values of five check digits spaced R digits apart over a time period corresponding to 4R+1. (For other interlacing techniques of this same sort, see Gallager,[39] p. 287.) Applied to moving mobile units, this interlaced code could correct the clustered errors which are due to multipath signal fades. This would serve as a convincing demonstration that simple error-control coding can overcome many kinds of channel variations without direct measurement of the channel and that appropriate error control coding can even substitute for diversity transmission in reducing multipath errors. This however would be at the cost of reduced channel efficiency due to the added redundancy required.

D. Typical System Error Calculations

In Chapter 2 we saw that impulsive noise causes higher error probability in digital transmission than Gaussian noise and that the majority of ambient mobile radio noise is impulsive in nature. We would now like to determine signal and noise levels which yield a "typical" signal-to-(impulsive)-noise ratio. With this signal-to-noise ratio we can refer to

CONTINUED
ON NEXT
FICHE

Fig. 16 (p. 35) and read off the "typical" probability of digital error for that signal-to-noise ratio and FSK modulation, both for non-fading and fading conditions.

Two cases for which "typical" signal-to-noise ratios have been calculated in this way are: direct digital modulation, and digital FM submodulation. Table 5 presents a signal power budget and "typical" error probabilities for a directly FSK-modulated 450-MHz signal without an intermediate submodulation, while Table 6 presents a power budget and error probabilities for FSK submodulation of voice FM equipment. Note that the signal-to-noise factor assumed for FM submodulation results in substantially lower probabilities of digital error under both non-fading and fading conditions. However it should also be noted that with an FM modulation index sufficient to attain such improvement, the modulation bandwidth is considerably less than the available r-f bandwidth. Digital channel capacity measured in bits per second is thus actually reduced by using FM submodulation, although the output signal-to-noise ratio and the corresponding digital error probability are improved.

Two items in the power budget tables which require explanation are "free space loss" and "excess path loss". Free space loss is the attenuation of signals with distance between two dipoles, neglecting the effect of terrain between transmitter and receiver. The formula for free space loss in decibels is:[43]

$$\alpha\Big|_{dB} = -33 - 20 \cdot \log_{10}(f_{MHz}) - 20 \cdot \log_{10}(d_{miles}).$$

Table 5

Power Budget for Direct Digital Modulation

Item	Typical	Standard Deviation
Transmitter power (50 watts)	47.0 dBm	0
Transmitter antenna gain (base station)[40]	10.0 dB	0
Transmitter line losses (100' of RG17/U at 450 MHz)[41]	- 2.0 dB	0
Free space loss (4 miles)	- 98.0 dB	0
Excess path loss	- 30.0 dB	±5 dB
Signal power at receiver	- 73.0 dBm	±5 dBm (A)
Man-made noise level[21,31]	-102.2 dBm	±6.7 dBm (B)
Signal-to-noise ratio (non-fading)	29.2 dB	±8.4 dB*

FSK Error Probability	Non-Fade	Fading
typical (29.2 dB)	2×10^{-5}	5×10^{-4}
one S.D. high (20.8 dB)	3×10^{-4}	4×10^{-3}
one S.D. low (37.6 dB)	$< 10^{-5}$	6×10^{-5}

*Standard Deviation (A+B) $= \sqrt{\text{S.D.}(A)^2 + \text{S.D.}(B)^2}$

Table 6

Power Budget for Digital FM Submodulation

Item	Typical	Standard Deviation
Transmitter power (50 watts)	47.0 dBm	0
Transmitter antenna gain (base station)	10.0 dB	0
Transmitter line losses (100' of RG17/U at 450 MHz)	- 2.0 dB	0
FM signal-to-noise improvement factor[42]	13.0 dB	0
Free space loss (4 miles)	- 98.0 dB	0
Excess path loss	- 30.0 dB	±5 dB
Signal power at receiver (effective)	- 60.0 dBm	±5 dBm
Man-made noise level	- 102.2 dBm	±6.7 dBm
Signal-to-noise ratio (non-fading)	42.2 dB	±8.4 dB

FSK Error Probabilities	Non-Fade	Fading
typical (42.2 dB)	$< 10^{-5}$	1×10^{-5}
one S.D. high (33.8 dB)	$< 10^{-5}$	2×10^{-4}
one S.D. low (50.6 dB)	$< 10^{-5}$	$< 10^{-5}$

Excess path loss is the empirical difference between predicted free space attenuation and actual measured signal attenuation over a base/mobile path, presumably due to the effects of terrain and man-made structures. As one would expect, this loss varies from city to city, urban to suburban conditions, etc. Some values which have been cited in the literature are shown in Table 7. We have assumed an excess path loss of 30 dB with a standard deviation of 5 dB, consistent with the values of Table 7. The excess path loss is a constant to which must be added the effects of fading.

Table 7

Literature Values for Excess Path Loss

Excess path loss dB (Standard deviation, dB)	Reference	Frequency
28-37	8	450 and 836 MHz 3.7 and 11.2 GHz
38	22	450 MHz
32, (5)	31	450 MHz
17, (3.5)	44	836 MHz
27, (6)	44	836 MHz

Note also that Tables 5 and 6 do not include antenna gain or feed-line losses at the receiver. The reason these were omitted is that the signal-to-noise ratio is unaffected by losses at the receiver so long as the internal receiver noise is much less than the external man-made noise, which Fig. 9 (p. 21) indicates is usually the case.

Digital error rates which have been cited in the literature for tests of mobile printers in urban areas are typically in the range 10^{-4} to

10^{-2} (references 7, 45, and 46), considerably worse than the values shown in Table 6. Error probabilities in the range 10^{-4} to 10^{-2} should only occur during severe signal fades (Rayleigh and/or shadow) or in local areas with unusually intense external noise. Although both multipath fading and impulsive noise can interfere with digital communication, multipath fading is probably the dominant cause of digital mobile radio error levels such as those reported in the cited tests. As has been discussed, diversity reception and/or error-correcting coding seem to be the best hopes for coping with errors when they exceed an acceptable level.

What is an acceptable level of error probability? This is a question that has no one unique answer, since it depends on what one is trying to do with the digital system (i.e., how bothersome errors are in a particular circumstance); also error probability for digital radio has to be expressed as a distribution over time and/or service area because of the variations in signal-to-noise ratio with these same parameters. The expected binary-error probability level in land-line data communications is 10^{-5} (one bit in error per 100,000), which corresponds to an average rate of one character error per 10,000 characters (assuming 10 bits per character), and this would clearly be acceptable as a goal for mobile communications. A binary error probability of 10^{-2}, which has been reported under certain conditions in some mobile printer tests, corresponds to 100 characters in error per 1,000 transmitted and would certainly be unacceptable as an average rate, although it might be encountered say 5% of the time even in a system where average rate was 10^{-5}. An average binary error rate of 10^{-4} (10 characters in error per 1,000 transmitted) probably represents the minimum acceptable performance for law enforcement use, but the goal should be higher.

CHAPTER 5

SUMMARY AND CONCLUSIONS

The central objective of this study was to examine the possible role of digital transmission techniques for improvement of law enforcement mobile communications, both as regard to operational advantages in command/control and automated information handling, and to more efficient use of the crowded radio spectrum. Necessarily, a change from present, well-established voice communications to the new, relatively unproven, and little-understood digital devices involves a complex mixture of technological, operational, economic, and regulatory issues, and all of these have been touched on in this report. Unfortunately the mixture of issues contains so many ramifications that despite the length of this report, it was not possible to treat all in equal detail or even to include every one that was identified in the study.

An overall conclusion, which was sensed at the beginning and reinforced as the study progressed, is that digital mobile communication is at a very early stage of development, and the technological capability that is available at present is but a small part of that which can be available in the future. A parallel, which perhaps cannot be followed exactly, exists in the transmission of digital data over telephone lines, which started out haltingly 15 or so years ago at 100-300 bits per second, and now is routinely conducted at 9600 bits per second. Also, proper equipment features and operational uses will take some time, including much more trial and experiment, to work out. It is therefore important that law enforcement communications planners not be too discouraged by some of the adverse test reports of the not too distant past, by operational shortcomings which they may see in present equipments, or even by cost (complex digital devices in high-volume production can be very inexpensive -- witness the electronic calculator), but instead energetically join in a continuing dialog with equipment manufacturers to steer digital development in the right directions for their needs.

It also became clear early in the study that because of the rapidly changing status of the technology, a simple survey of existing equipments and usages, while valuable for some purposes, would not really address the central objective stated at the beginning of this summary chapter. A large part of the study and this report have therefore been devoted to identifying factors which presently limit the speed and accuracy of digital mobile communication, and to outlining, where possible, techniques which are or may be available for overcoming these limitations in the not-too-distant future. Much of the description of the problems and solutions is necessarily technical and mathematical in nature, but an attempt has been made to state results in practical form. Briefly, the major conclusions may be stated as follows:

1. Digital data transmission with acceptable error probability requires about the same mean signal-to-noise ratio as good-quality voice transmission, however digital error probability is much more sensitive to the large, instantaneous variations from the mean that presently result from fading and man-made noise.
2. Multipath propagation leads to Rayleigh-distributed amplitude fading of land-mobile signals and analysis of typical measured noise levels and signal levels indicates that multipath fading is the dominant error-producing mechanism.
3. Either of the two available impulsive noise models (telephone or atmospheric) is a more realistic model than the Gaussian noise

model for the urban mobile radio noise environment and, for the same mean signal-to-noise ratio, digital error probabilities are much worse in impulse noise than in Gaussian noise.

4. While there are differences between them, the particular digital modulation method (PSK, DPSK, FSK, etc.) is of much less importance in determining error probability than the noise environment or the fading characteristics of the signal.
5. Since very little can be done about the noise environment for mobile communications, the only potential means of improving the signal-to-noise ratio of the radio channel for digital transmission is to use some form of diversity reception to reduce the variance of multipath fading.
6. Either space diversity (multiple antennas) or frequency diversity (multiple frequencies) should be practical for vehicular receivers, but only frequency diversity has any possibility of use for portables. Frequency diversity, which is common in fixed-base radio communications, seems to have received almost no attention for land-mobile use because of spectrum congestion considerations. However, use of two land-mobile channels (approximately 1-MHz separation) for frequency diversity might yield such an improvement in digital data and error rates that there would be a net improvement in spectrum utilization, i.e., two channels used jointly in this way could have a significantly greater capacity than the same two channels used separately. It is recommended that both space and frequency diversity be implemented and their error-reducing effects compared.
7. As a minimum, cyclic error-detecting codes with message retransmission as necessary are essential for assuring reliable reception of digital messages. More complex, but still relatively simple convolutional coding can correct isolated errors, and with code interlacing, even the burst errors caused by multipath fading. It is recommended that experiments be conducted to determine whether an interlaced error-correcting coder on a single channel can substitute for multiple diversity

channels and yield a similarly improved error rate without the additional spectrum or equipment requirements of diversity transmission.

8. Digital submodulation of voice FM equipment radios, as in most present digital systems, has operational advantages, but digital performance is compromised by the bandwidth, threshold, phase, and noise characteristics of the FM equipment. Other forms of modulation, perhaps requiring new channel specifications, may be necessary for full realization of digital capabilities.

9. Voice transmission with a 30 db signal-to-noise ratio is possible over a digital channel with a data rate of 30,000 bits per second and a binary error probability of only 10^{-3}. This could be achieved with a 50-kHz r-f channel, i.e., two adjacent 25-kHz channels used as one channel. If such high-speed digital channels were available, it could result in a net improvement in spectrum utilization, plus the possibility of alternate voice/data usage.

10. Random-input interrogration of a mobile fleet appears to give a much faster access time than sequential polling interrogation, but it also reduces the number of mobiles which can be accomodated in a digital mobile network. The question of best polling procedure for a given system thus depends on the particulars of the system and its desired functional performance.

APPENDIX A

ANALOG TRANSMISSION OVER A DIGITAL CHANNEL

The main body of this report is entirely concerned with the transmission of digital information over analog channels, such as voice FM equipment. This appendix examines the reverse problem: given a digital channel as characterized by its data rate, R bits per second, and its binary error probability, P, is it possible to transmit analog signals such as voice over the digital channel and, if so, how much distortion is introduced by the digital conversion/transmission process? Also, what are the bandwidth requirements? The answers to these questions are central to determining whether it is better to construct an analog system which sometimes carries digital data or to construct a digital system which might carry analog signals.

The starting point is the uniform sampling theorem for band-limited signals:[33]

> "A band-limited signal which has no spectral components above a frequency B cycles per second is uniquely determined by its values at uniform intervals less than 1/2B seconds apart."

To represent these continuous analog sample values with a digital signal it is necessary to discretize the sample values and transmit them as N bit binary numbers. Figure A-1 illustrates the operation of the digital sampler/quantizer.

It is possible to calculate the mean square error of the quantizing process (i.e., the average quantization noise power) when the quantization is due to roundoff as in Fig. A-1.

$$E\{n_1^2\} = \int_{\frac{\varepsilon}{2}}^{\frac{\varepsilon}{2}} \frac{1}{\varepsilon} n_1^2 dn_1 = \frac{\varepsilon^2}{12} .$$

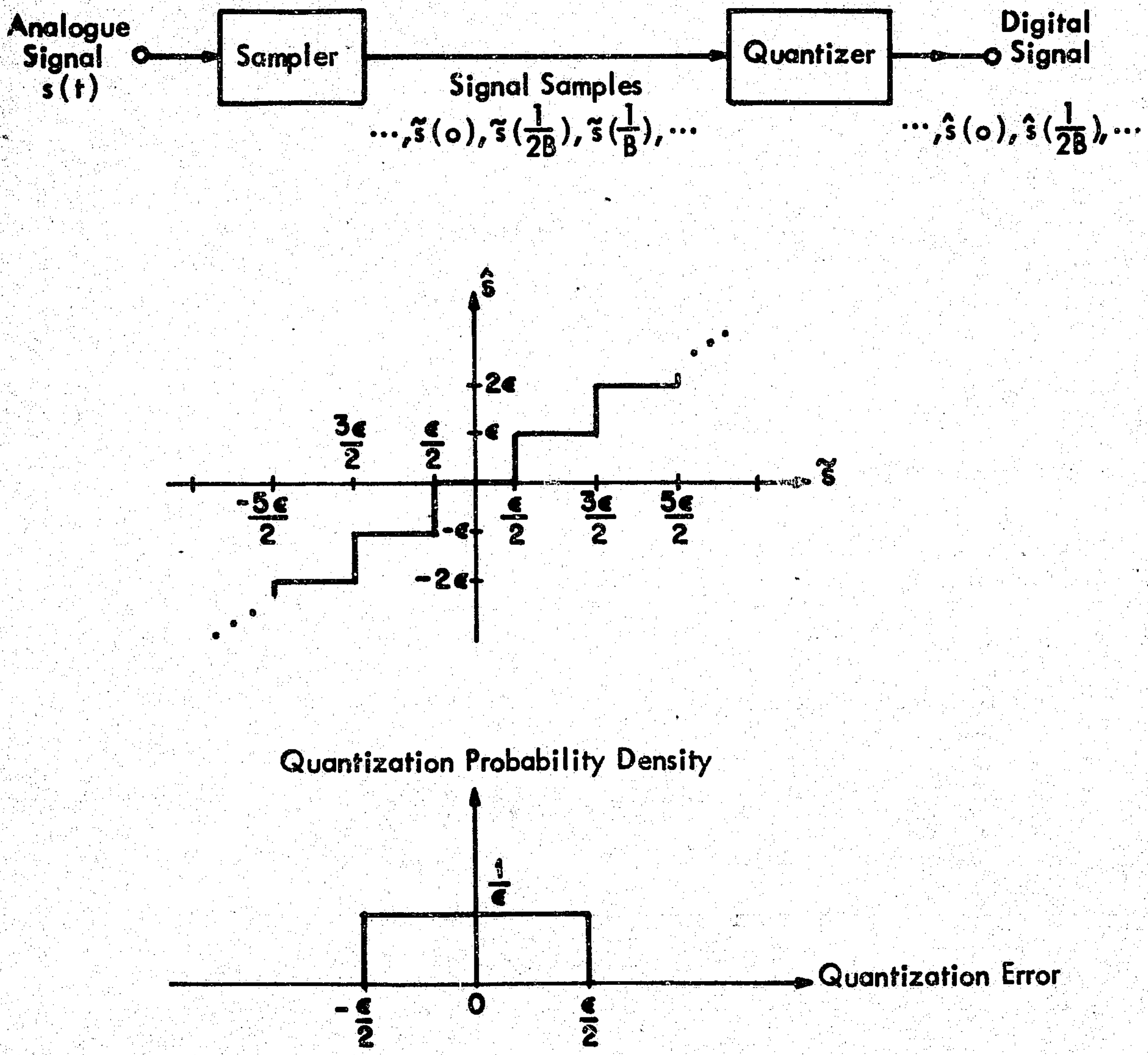


Fig. A-1   Sampling and Quantization of an Analog Signal

For N - bit binary quantization

$$E\{n_1^2\} = \frac{4^{-N}}{12} .$$

In addition to the quantization noise, a second source of noise is due to the probability of binary error. An error in the jth most significant bit of an N bit number produces an amplitude error of 2^{-j} or a noise power contribution of 4^{-j}. (P is the probability of binary error.)

$$E\{n_2^2\} = \sum_{j=1}^{N} P4^{-j} = P(\frac{1-4^{-N}}{3})$$

Adding these two noise powers we obtain the total noise due to binary quantization and bit error probability.

$$E\{n^2\} = E\{n_1^2\} + E\{n_2^2\} = \frac{1}{12} 4^{-N} + P(\frac{1-4^{-N}}{3})$$

This is the analog noise power caused by digital transmission of a unit amplitude signal. If the signal is sinusoidal, its time average power is 1/2 and the resulting signal-to-noise ratio can be calculated.

$$\begin{aligned} \text{SNR(dB)} &= 10 \log_{10}\left(\frac{\text{average signal power}}{\text{average noise power}}\right) \\ &= 10 \log_{10}\left[\frac{1/2}{\frac{1}{12}4^{-N} + (\frac{1 - 4^{-N}}{3})}\right] \\ &= 10 \log_{10}\left[\frac{6.4^N}{1 + 4P(4^N - 1)}\right] \end{aligned} \qquad \text{(A-1)}$$

Using Eq. A-1, constant-value loci of SNR have been plotted in Fig. A-2 as a function of P and N. Also shown in Fig. A-2 is a dashed line obtained by setting $E(m_1^2) = E(m_2^2)$. Above this line bit error noise

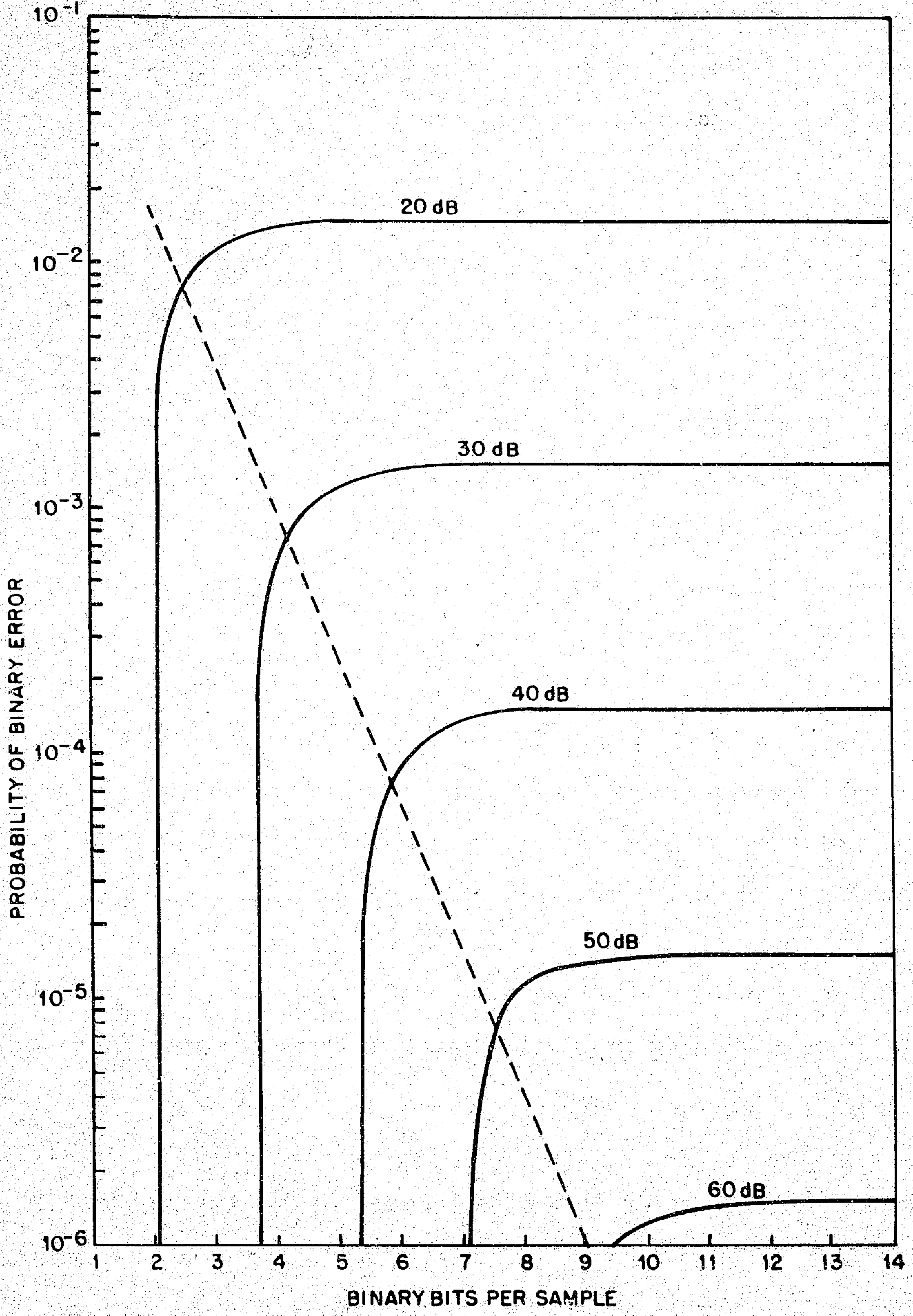


Fig. A-2 Signal-to-Noise Ratio for a Quantized Analog Signal as a Function of Binary Error Probability and Number of Bits per Sample dominates; quantization noise dominates below it. Since the best bit error probability that can be expected is 10^{-5}, it is seen from Fig. A-2 that there is no advantage in using more than seven bits of quantization.

With these results we have already determined quantitatively the distortion (i.e., noise power) introduced by the digital transmission of analog signals. To determine the required bandwidth we must recall the results of Chapter 3: a realistic bandwidth for the transmission of R bits per second is R Hertz ($R = W$ where W is the r-f bandwidth or the two-sided baseband bandwidth).

Given the bandwidth B (Hertz) of the analog signal and the acceptable signal-to-noise ratio we can find the required binary word length N from Eq. A-1 or Fig. A-2. From the uniform sampling theorem we find that a data rate $R = 2BN$ bits per second is needed, and the resulting realistic bandwidth is 2BN Hertz.

In this fashion we can compare PCM voice transmission over a land mobile radio channel with FM analog transmission. Assuming B is 3 kHz for voice signals and that a signal-to-noise ratio of 30 dB is desired (equivalent to FM quality above threshold), the required binary word length is five bits. Therefore the required data rate is $2BN = 30{,}000$ bits per second and the two-sided r-f bandwidth is at least 30 kHz, which would require a channel spacing of 50 kHz. This is the same sort of wide-band digital channel (two present 25-kHz channels merged into one) that was discussed in Chapter 3.

Off-hand, digital transmission of voice does not look attractive because of this bandwidth requirement. However if wide-band channels are ever established for high-speed digital data (30,000 bps), the possibility would exist for alternate transmission of digitized voice over such channels.

APPENDIX B

DISCUSSIONS WITH MOTOROLA

1. Introduction

This is a combined report of two separate discussions with representatives of Motorola Communications and Electronics, Inc. In the first meeting, J.E. Ward visited the Motorola plant in Schaumburg, Illinois, on October 27, 1971, and met with Mr. Steven Adler, Engineering and Sales Manager for State and Local Government Markets, and Mr. Warren Henderson, Systems Resources Marketing Manager. In the second meeting, Mr. Adler and Mr. William Borman (Manager for AVM Systems) visited M.I.T. on November 11, 1971 and met with Professor J.F. Reintjes and Messrs. J.E. Ward and T.C. Kelly.

These two meetings covered the emerging field of digital transmission and computer-based information handling in law-enforcement systems, both in the mobile/portable radio environment and in local, state, and federal inter-computer networks. Also discussed were the technical issues in digital radio transmission, automatic vehicle monitoring (AVM) systems, and probable equipment development timetables for the new 900-MHz band recently allocated by the FCC.

2. General System Issues

To lay the groundwork for our meetings we described the Electronic Systems Laboratory's project with the National Institute of Law Enforcement and Criminal Justice to study existing digital communication and information-handling techniques as well as to locate communication/information bottlenecks where digital techniques may be especially helpful in law enforcement. In turn, the Motorola representatives described Motorola's involvement in law enforcement communications at both the component equipment level (mobile radios, hand-held portables, mobile teleprinters) and at the system level (automatic vehicle location--both fixed route and random, microwave communications, computer-based dispatching, and integrated networks).

A particular system discussed in the latter context was the SMARTS (San Mateo Automated Rapid Telecommunications System) Communication Network which Motorola is installing. This is a self-contained, computer-based, store-and-forward message system utilizing both wire links and the San Mateo County microwave (Motorola) network for transmission. The system currently has 19 teleprinter terminals, but will be expanded to 40. SMARTS operates as a sub-system of CLETS (California Law Enforcement Telecommunications System), and thus provides ready access to the 450 CLETS terminals, and through it to the FBI's National Crime Information Center (NCIC).

The tone of this part of the discussions indicated that Motorola is very much involved at all levels of the law-enforcement communications problem, and has spent a good deal of time in examining the problem from an overall system viewpoint. They indicated their feeling that existing local police communications equipment is in general quite adequate and that the biggest problems for the immediate future are:

(a) how to coordinate the multitude of local, state, and national communications and information systems into a smoothly operating whole (i.e., the network problem); and

(b) how to provide the needed expansions in radio communications capabilities (mobile and portable) in the face of spectrum congestion and limited financial resources (best utilization of spectrum resources, and cost effectiveness).

3. Spectrum Problems

Some relief in the 450-MHz band will be realized by the FCC reassignment of the lower UHF-TV bands in the major cities, but the Motorola people felt that the non-interference rules would seldom permit operation anywhere near the maximum power and antenna height limitations (1,000 watts and 500'), and that performance may thus be marginal compared to the present 450-MHz band.

The new 900-MHz mobile band (reassigned from UHF-TV Channels 70-83)* offers a real break in the spectrum log-jam for the future, but is not immediately useful. One problem is that of low power output of solid state devices at these frequencies, although this is now being effectively solved. Another factor is that the planned use of this new band is still being considered by the FCC under Docket 18262, with various organizations proposing everything from extension of the simple channel pair concept (as in the present 450-MHZ band), base station channel trunking arrangements (managed groups of channel pairs), and rate regulated common carrier systems for an entire urban area, using both trunking and cellular concepts. Final equipment designs must await the resolution of these issues; namely, how this new band is to be used.

Since spectrum-space relief as discussed above will be slow in coming, Motorola is also actively looking to the use of digital techniques to improve the use-efficiency of present channels, as discussed below.

---

*Actually 806-902 MHz, and 928-947 MHz. This provides an additional 115 MHz, about a three-fold increase in mobile spectrum.

4. Digital Technology

In the two meetings, the Motorola people discussed a number of issues in connection with digital transmission:

(a) There is a severe RF noise problem in cities--as high as 50 microvolts per meter in New York City--and strong transmitters on adjacent channels cause intermodulation distortion. The ± 5 kHz, FM deviation limit in a 25-kHz channel is intended to keep adjacent-channel interference within acceptable limits, but the resulting deviation ratio is often so small that the advantages of the FM capture and threshold effects are minimized (increasing the possibility of adjacent-channel interference, and decreasing signal-to-noise ratio, except under very strong signal conditions. Further channel splitting (to 12.5 kHz) would increase the severity of these problems. Motorola's approach to these channel-noise problems is to use best possible receiver designs--sensitive receivers with FET front ends and sharp quartz IF filters to reduce adjacent channel interference--but this is of little help against noise and interference components (including multipath) that are "on-frequency".

The gist of this part of the discussion was that the radio channel often represents a poor medium for digital transmission, and that work still needs to be done in modulation and coding techniques to improve the immunity of digital signals to noise and interference, and in cellular and/or diversity arrangements to improve the channel.

(b) They said that they have used or are investigating at least a half-dozen digital modulation techniques. They mentioned one technique which yields satisfactory transmission of 100 bits per second at signal-to-noise ratios as low as 6 db (12 db is considered the minimum acceptable for voice, and most digital techniques need at least 20 db). This technique uses sequential, decimally coded tones transmitted at quite a slow rate--30 per second--but since a decimal digit represents about 3.3 bits, the effective bit rate is 3.3 x 30 = 100 bps. The effectiveness of this technique in combatting noise obviously arises from the longer recognition time per item of transmitted information--33 ms. as against 10 ms. if the bits were transmitted in binary form. The problem with this technique is that 100 bps is too slow for many purposes, and it is difficult to do multi-tone recognition at any faster rate.

The CTA/Monitor bus location system for Chicago system operates at 2000 bps, using a form of pulse-width modulation. There have been numerous difficulties with errors since the tests began in mid-1970, but many of these were due to electrical noise sources in the buses and mobile radio component problems which have since been corrected. More recently, it was discovered that the telephone-line connections from the satellite receivers were distorting the digital signals, and these are in process of being improved. (Despite a number of inquiries before, and after these meetings, we have been unable to obtain any information from Motorola on the error rates actually being achieved in practice in this system.)

(c) Motorola feels strongly that voice and digital signals should be on separate channels, i.e., that overlay systems will be unacceptable because of the annoyance of hearing digital tones intermixed with voice. This of course gets into the spectrum congestion question--does this double everyone's channel requirements?

(d) Many feel that 100 bps (10 characters per second) is too slow for mobile printers, particularly when lengthy printed responses result from an inquiry, and that much faster output rates are needed. Motorola feels that a 100-bps rate may still be satisfactory if a more judicious choice of operating modes is used, such as generating a full printer response only on a "hit".

(e) Nationwide, about 80 percent of patrol cars are operated on a one-man basis, thus complete reliance on printers or displays for dispatch is difficult because they can't be read while the car is in motion.

(f) Portables represent another problem for digital systems, and their use is on the increase (already, eight U.S. cities use <u>only</u> portables). Digital input from portables will soon be feasible, but digital output capability is a long way off. Computer-generated voice response appears to be the only immediate solution, and Motorola mentioned they had heard of some tests of this technique in a police radio system. Response "only on hits" was mentioned as desirable to reduce channel time.

(g) Motorola's stated position is that they are actively pursuing digital mobile radio technology, but that they are not selling it as the answer to all communications problems. They interact with each system requirement as it arises and feel that it will gradually gain acceptance in applications where it clearly is of advantage as compared to all-voice techniques.

5. AVM Systems

Motorola has developed a new AVM system (first announced in mid-1971) which operates on a phase-ranging basis. The base-station transmits (using FSK modulation) the code of the vehicle it wishes to locate. The vehicle then responds by transmitting 64 cycles of a 2700-Hz tone, which is picked up by several satellite receivers and transmitted to the base station over telephone lines for phase comparison. A demonstrated accuracy of 800' was cited. The time per fix is 30 MS, i.e., 33 different vehicles can be located per second. The system may be calibrated at any time (even as often as every "fix") by interrogating one or more fixed radio transceivers.

(Note: This new Motorola AVM system seems considerably simpler than the Raytheon system that was tested in Boston. That system had the vehicles repeat--on another channel--a tone transmitted by the base station, made phase comparisons at each satellite receiver site between the master base-station tone and the vehicle-repeated tone, and transmitted these measured phase differences digitally over telephone lines to a base-station computer for location calculations.)

6. General Comments

Motorola sees the need for independent organizations to look objectively at the land mobile "bandwidth-modulation-channel assignment" problem and recommend improvements such as digital modulation to alleviate the congestion and interference. They are most interested in the results of our work, and in further discussions later on.

APPENDIX C

DISCUSSIONS WITH GENERAL ELECTRIC

1. Introduction

On January 27, 1972, Messrs. J. E. Ward and T. C. Kelly of the Electronic Systems Laboratory visited General Electric's Mobile Radio Department in Lynchburg, Virginia, hosted by Mr. John A. McCormick with whom several letters had been exchanged earlier.

Most of the morning was devoted to a roundtable discussion of recent developments in land mobile and public safety vehicular communications with the following General Electric personnel:

John A. McCormick - Consultant
Robert T. Gordon - Manager, Advance Development Eng.
N. S. Cromwell - Manager, Major Accounts
Ralph D. Abrams - Manager, Major Direct Markets
James E. Ardery - Manager, System Products Planning
Paul E. Perrone - Public Safety Systems
Ronald Sission - Superintendent of Engineering (Toronto System)
Robert Fruin - Diginet 1600 Software (Toronto System)
Fred Arnold - GE Pac 30

Mr. Ward briefly summarized the Electronic Systems Laboratory's activity in digital vehicular communication through the Project CARS (Dial-a-Bus) program and, more recently, through the study grant from the National Institute for Law Enforcement and Criminal Justice for possible law enforcement applications of digital communication technology. The GE people were interested in the present status of Project CARS (a copy of the final CARS report was left with them) and they would appreciate a copy of the final report of the NILECJ report.

2. System Topics

General Electric is one of the four largest manufacturers of mobile (vehicle) and portable (hand-held) radios. They stated that portable radios in particular have been a rapidly growing field and that the concept of "a radio for every officer" is reshaping law enforcement communications. Most recently, GE, like most mobile equipment manufacturers, has developed a digital communication capability as demonstrated in their installations for the Los Angeles County Mechanical Department and the Toronto Police Department.

The Toronto system is currently under design and construction, and is expected to be operational in early 1973. The heart of the concept is dynamic management of channel usage, both to provide maximum utilization of the 12 available channels under any situation, and also to permit "channel-hopping" to increase the difficulty of clandestine monitoring of police communications. All radio equipment in the system will have 12-channel capability, with provisions for remote control of the transmitting and the receiving channels for a particular unit at each instant of time by means of digital signals from the control center.

There will be six base-station transmit/receive sites located in different parts of the city, and each will have two transmitters and two receivers. All base stations can be operating simultaneously on the same or different channels. A total of 713 vehicles will be equipped, of which about 80 percent may be in use at one time. The mobile radios will be standard 12-channel units, with external digital output and input equipment connected through the normal audio microphone and discriminator jacks.

The control center will use a GE Diginet 1600 controller in combination with a matrix switch to assign the 12 available channels among operations consoles and mobile units, and its channel-switching commands will be sent out as a differential phase-shift tone burst (200 millisecs at 2400 bits/sec) at the beginning of a voice transmission. A GE Pac 30 computer will handle channel allocation and can command the controller to scramble the channel assignments and/or to assemble certain groups on a single channel. The radio operators will not have to concern themselves with channels or digital data — they will be properly connected automatically.

This computerized switching system is a significant advance in the field, but it should be noted that this is not a digital communications system; it is a voice system with digital channel control. Since only the brief control bursts (200 ms) are digital, GE has not felt that it was necessary to use polling techniques to avoid mutual interference. Also they are not very concerned about errors in these control bursts, feeling that they will have good signal-to-noise ratios everywhere. Although each city zone has its own base station, they expect almost city-wide coverage from any of them. The prime consideration in the choice of 2400 bps as the digital transmission rate for the control bursts was to shorten the "beep" tone that precedes each transmission so that it will be heard as a "clock" rather than as a tone. They recognize the higher probability of error at 2400 bps, and said that if it were not for the human annoyance factor, they would have preferred to use a slower digital bit rate with a lower error probability. We gained the impression that the actual error rate in practice remains to be measured.

The GE people said that they are not pushing digital mobile radio at this time, except possibly printers and audio-encoded data for a few special applications. The real problems which they see facing digital communications are a lack of convenient input and output devices for busy vehicle drivers (as convenient as microphones and loudspeakers), necessary digital compatibility for hand-held portables, and frequent data fadeouts (shadowing or multipath). On the other hand, they hope rapid digital signaling methods will eventually be able to reduce the 88 percent of voice transmitting time now used for routine reporting and thus ease channel congestion.

The longer-term future of land mobile radio was seen to balance on the new 900-MHz allocations which contain three times as much bandwidth as is now in land-mobile use altogether. GE has done extensive field tests at 900 MHz for the FCC and their final report will be available soon. Major problems are low power output and multipath fading, but GE feels that it is a usable band for short-range communication. There was some discussion of the various filings by AT&T, Motorola, and GE under FCC Docket No. 18262, which will determine the rules for use of the 900-MHz band. GE would like to see channel trunking on a user-by-user basis, rather than large common-user systems such as proposed by AT&T.

3. <u>Technical Discussions with Mr. Robert Gordon</u>

In the afternoon we met with Mr. Robert Gordon to discuss the detailed technical problems which were set aside at the larger morning meeting. Such topics included signal fading, noise and bandpass characteristics of FM equipment, diversity techniques, and spectrum conservation.

To account for random signal fading, GE uses a probabilistic specification: a log-normal probability distribution for the median signal levels (long-term "shadow" fades) and a Rayleigh probability distribution (short-term "shadow" fades). With these assumptions, they calculate that an 8-dB median SNR will provide an adequate signal 90 percent of the time and essentially no signal for 10 percent of the time (because of the FM threshold effect). Increasing power to raise the median SNR improves the 90 percent figure, but the improvement quickly becomes uneconomical, especially at 900 MHz where power is at a premium.

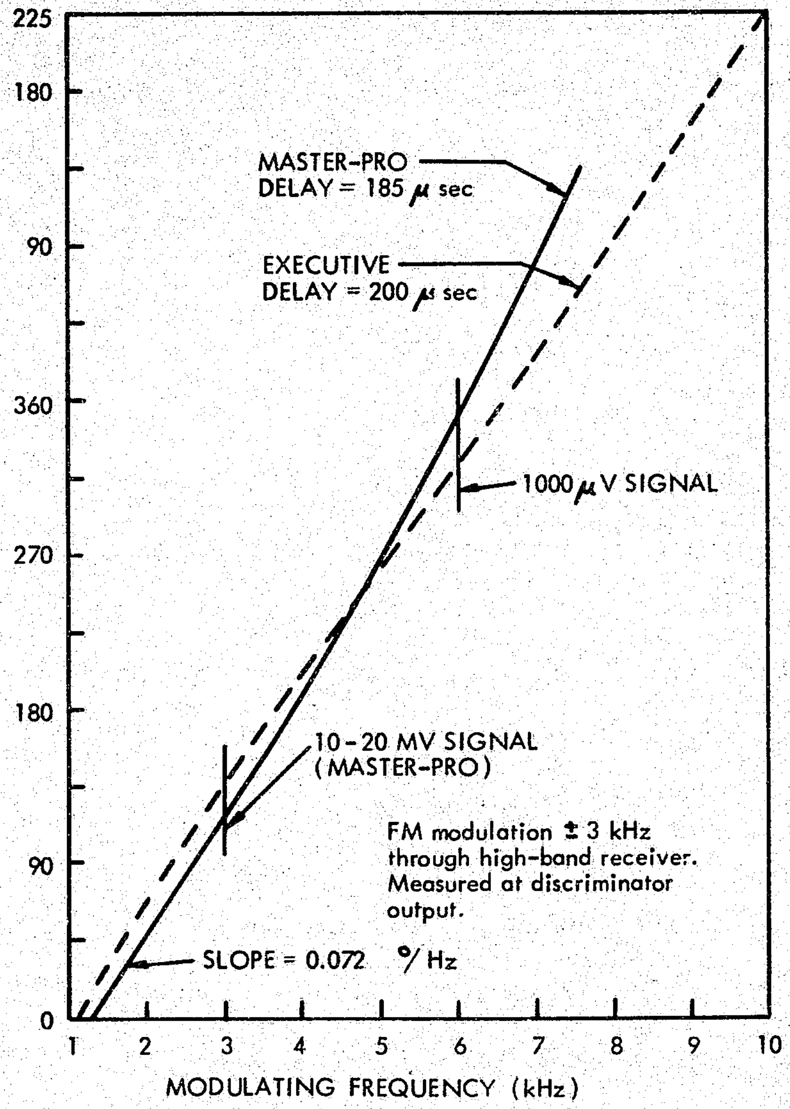
The magnitude characteristics of the audio bandpass in FM mobile equipment are quite similar to those of telephone channels, but the phase response is much smoother and group delays are smaller. Mr. Gordon promised to send actual measured magnitude/phase plots for our use in calculation.* GE has analyzed noise in FM receivers using the anomaly or "click" method# in which periodic pulses appear in the receiver output even for very strong signals (background hiss). Mr. Gordon has verified the existence of anomalies even on strong signals and he feels that this characteristic of FM receivers may interfere with high-speed digital communications. He said that their tests to date indicate that impulsive ignition noise is no more severe at 900 MHz than at 450 MHz.

The last general areas of discussion with Mr. Gordon were diversity techniques and spectrum conservation. GE has experimented with space diversity to improve the signal-to-noise ratio in voice communications, but

---

*This graph was received and is shown in Fig. C-1.

#For an explanation of the "click" method, see, for example, Wozencraft and Jacob, <u>Principles of Communication</u>, p. 661.



FM modulation ± 3 kHz through high-band receiver. Measured at discriminator output.

Redrawn from curve dated 2/9/72 by R.T. Gordon, General Electric Mobile Radio Department.

Delay figures are for the absolute delay of a pulse through the transmitter and receiver. The slope extends in a straight line down to 150 Hz.

Fig. C-1 Phase and Delay for GE Mobile Radios has concluded that for voice communication, the improvement is not worth the additional cost. For digital communications, however, the improvement may be necessary and then, as Mr. Gordon said, "Diversity must be considered an expense of digital communication." He said that another problem with space diversity is the need to adjust for RF and modulation phase coherence, citing GE experience in the New York Thruway FM microwave system in which both phase delays and phase equalizers have been found to be necessary.

The discussion of spectrum economy focused on channel separations in the land mobile service. Mr. Gordon feels that further channel splitting (i.e., to 12.5kHz) could raise severe problems if it results in smaller FM deviations (this would almost eliminate the FM threshold). Also, frequency stability could be a problem because the best available crystals are ± 2 parts in a million, or ± 2 kHz at 900 MHz. Other methods of spectrum reuse, such as time or zone switching may be used, but further frequency subdivision appears undesirable. Finally Mr. Gordon pointed out that straightforward transmission of digitally encoded voice requires wide bandwidths (from 6 kHz to as much as 40 kHz for a 3-kHz voice signal, for example). Thus unless some form of data compression can be employed, the bandwidth requirements are 2-13 times that for analog voice transmission. He could see little prospect that digital transmission of voice, such as is now gaining favor in the telephone system, will be employed in mobile radio.

4. Plant Tour

After our technical discussions, Mr. McCormick took us on a tour of the production facility where we were able to observe all stages of assembly of mobile and portable radios, microwave repeaters, voting receivers, and the integrated circuit and quartz crystal facilities.

Finally, we met briefly with Mr. Glenn Peterson, General Manager, GE Mobile Radio Department; Chairman, Land Mobile Section, EIA and expressed our appreciation for the courtesies extended to us on this visit.

APPENDIX D

DISCUSSIONS WITH REPRESENTATIVE GREATER BOSTON POLICE DEPARTMENTS

This appendix describes discussions that were held with four Greater Boston police departments. The purpose of these visits was to find out about their present radio communications operations, and to elicit comments on how digital radio communications might fit into their plans for the future. The four departments visited were: the Boston Police Department, the Metropolitan District Police, the Cambridge Police Department, and the Lexington Police Department.

1. Boston Police Department

One October 14, 1971, Professor J.F. Reintjes and Messrs. J.E. Ward and T.C. Kelly visited Boston Police Headquarters and met with Mr. Steven Rosenberg, Director of Planning and Research. The purpose of this meeting was to discuss the present communications setup of the Boston Police Department, any particular communications problems with the present setup, and the role that digital communication techniques might play in the future. On December 16, 1971, Mr. Kelly met with Sgt. Leroy "Bud" Hunter, the Communications Officer for the Boston Police Department, who is also the New England Frequency Coordinator for law-enforcement communications. Topics discussed included more details on the BPD radio System, plus general discussion of radio coverage and frequency allocation problems.

a.) Communications Research Projects

Mr. Rosenberg mentioned five local communication projects of importance, all funded to some extent by the Law Enforcement Assistance Administration (LEAA) through the Governor's Committee on Law Enforcement and Administration of Justice.

- The Boston Police Department was in process of upgrading its command center and radio setup (see paragraph b. below) and its consultant organization, Urban Sciences, Inc., has recommended installation of an AVM system.
- The Greater Boston Police Council (Boston and 13 neighboring police departments) had contracted with Urban Sciences to study the feasibility of coordinating dispatching procedures and radio channels among the participating departments.
- The Massachusetts State Police had contracted with Mitre Corp. to recommend improvements in their mobile radio communications.
- A municipal Radio Project was assessing the radio communication requirements of cities in western and central Massachusetts.

b.) Present BPD Communications and Plans

Mr. Rosenberg and Sgt. Hunter indicated that the BPD communications capability was pretty good, although they were in process of making a number of needed improvements. Boston had been using two dispatch channels with city-wide coverage (46 square miles) but was in process of expanding to an eight-channel zoned setup, using some of the 38 new channel pairs that have become available through the 1971 FCC reallocation of UHF-TV channels 14 and 16 in Boston. The new channel setup is part of a new computerized command-control console being installed by Motorola. In the eight-channel setup they will use four for mobile units (one each for three geographic zones and one city wide), and four for portables. There will be all-call capability on all channels.

Boston has a total fleet of 364 vehicles, of which about 150 are active at one time. The BPD presently has 400 portables, and has plans to acquire about 300 more. Mr. Rosenberg said that they would like about 2800 portables (one for every duty patrolman) but that the cost per portable would have to drop from the present $960 level to about $250 before such a mass equipment program would be feasible.

The BPD has been operating both 150-MHz and 450-MHz equipment, with five 150-MHz channels and 14 450-MHz channels (four of which are shared with other city services). They will probably drop use of 150-MHz in the future as the additional 450-MHz channels become available, and as the older 150-MHz equipment is retired (the replacement cycle is five years). They experience some intermodulation interference, but multipath fading has not been a problem, primarily because of high transmitter powers (20 watts for mobiles, 100 watts base) and a good satellite receiver arrangement (three at 150-MHz, five at 450-MHz). Mr. Rosenberg said that he could easily communicate from his home 25 miles south of Boston with a portable.

A study performed for the Boston Police Department by Urban Sciences, Inc., recommended installation of an AVM system. Boston had participated in tests of a Raytheon phase-ranging AVM system, but felt that its performance was inadequate: it yielded 1200' accuracy 90% of the time. They also mentioned tests by Sanders Associates of a triangulation AVM system which apparently had some success at 150 MHz, but was inaccurate at 450 MHz because of multi-path problems. The new Motorola phase-ranging system promises 800' accuracy 95% of the time, and Mr. Rosenberg feels that this accuracy is the minimum that they would want from an AVM system, and was hopeful that the Motorola system could be tried out in Boston as part of the new Motorola command and control sonsole installation. The hoped-for advantages are improved response time in getting a unit to the scene, and better management of the vehicle fleet.

He also expressed interest in eventually including portables in an AVM system so that the location of foot patrolmen can be established. A particular problem mentioned in this regard is the control of large crowds in restricted areas. When demonstrations such as occurred last year on Boston Common are in progress, they would like to be able to pinpoint the location of each officer to within 50-100 feet. This accuracy may be possible with ranging transmitters sited to cover just the desired area, such as Boston Common.

c.) Discussions on Digital Issues

Mr. Rosenberg indicated that the BPD has had little interest in vehicle digital printers. One of the major reasons is that unlike some other police departments, they like every policeman on duty, whether in a car or on foot, to hear all dispatches, both to be aware of what's going on and also for mutual aid. Mr. Rosenberg cited the case where a foot patrolman might be right around the corner from a holdup and be able to respond faster than the vehicles dispatched to scene (Boston will lose some of this "party line" aspect as it goes to a three-zone system, but can still issue general alerts in such cases by using the all-call channel.)

Other problems cited in connection with printers are the difficulty of their use in one-man vehicles, where it is impossible to read a message when the vehicle is in motion, and the present impossibility of digital communications with portable radios.

Mr. Rosenberg mentioned a number of other issues in connection with digital communications:

> direct access of computer information from a patrol car is desirable but he felt that existing systems need improvement,

particularly a shorter transmission time (higher digital transmission rates) and better user-oriented design of mobile devices (keyboards, printers, displays, etc.);

- the security advantage of digital communication is considered unimportant by the BPD except in burglarly or narcotics operations;
- the desirability of completely separating voice and digital communications to prevent both voice listener irritation from digital signals and digital errors from voice interference (apparently he was ruling out an "overlay" digital system for Boston);
- the cost of digital equipment represents a barrier to its use;
- and finally, he felt that digital error rates should not be a problem in Boston because of the excellent radio coverage they now have as a result of high base-station power and the number of satellite receivers.

d.) Frequency Allocation Problems (Sgt. Hunter)

High band (150 MHz) is filled throughout New England but outside the Boston area there are some available channels in the 150- MHz band and several in the 450-MHz band. New uses of low band (30-50 MHz) are being discouraged because of skip problems and ignition interference. In fact, a number of present low-band users will probably shift to the 450-MHz band for these reasons (Mitre's study for the Mass. State Police recommends a shift from low-band to 450-MHz).

In Greater Boston, every available channel in all bands is presently allocated, and many users must share channels. Sgt. Hunter said that the use of tone squelching is being recommended for shared channels to eliminate reception of unwanted transmission. He also mentioned one undesirable situation in New England where two large-city police departments only 50 miles apart must share a common channel: Hartford and New Haven.

Relief (for a time) from the present channel congestion will be afforded by the FCC's reallocation of UHF-TV channels 14 and 16 in Boston which will provide 38 channel pairs, it is estimated that these new channels will satisfy demand for at most five years. For the long term, there is the possibility of further channel splitting (the subdivision of the present 25-kHz FM channels into 12.5-kHz narrow-band FM or single-sideband channels)*, plus use of the new 900-MHz band.

2. Metropolitan District Commission (MDC) Police

On December 2, 1971, Messrs. J.E. Ward and T.C. Kelly visited Captain Tobin at the MDC Lower Basin Police Station, Boston, to discuss MDC radio communications. The MDC police jurisdiction covers the entire Greater Boston Area (a radius of 12-15 miles), but except in general emergencies or "hot chases", only on the system of parkways, parks, and recreational facilities that are under MDC jurisdiction. Each of the eight MDC stations has its own vehicle fleet, but all share one central dispatch center and base station R/T. For Captain Tobin to transmit a message to one of his vehicles, he must use telephone or teletype to send the message to the dispatch center, which will then put it out on the air when time is available. The stations do not have transmitters, but do have receivers tuned to the base station and vehicle channels. Vehicles can usually be heard at the station, but not always. The problem here is that the station receiving antennas are not particularly high. Vehicles can always be heard at the dispatch center, however, and the messages relayed to the stations as necessary. This can cause delays in field reports. It was not clear whether the dispatch center always relays vehicle transmissions to the proper stations via phone or teletype, or only upon request when a station is unable to hear a particular vehicle response.

Most MDC patrols are one-man, and officers are often some distance from their vehicles, particularly when working in the parks and recreational areas. Captain Tobin is thus very interested in vehicle printers to record messages, and made one test (inconclusive) a year or two ago. At the time of the visit, he said that he hoped to obtain a Highway Safety Project grant to experiment with six vehicle repeaters (Mobile Radio Extenders) for out-of-car situations. He also mentioned the need for more portables for communication with MDC patrolmen on traffic-direction duty. From his office window, one could see an MDC officer a half-block away in a traffic box and Captain Tobin said that the only way to reach him was "open the window and yell".

The MDC police use three low-band (39-MHz) radio channels: dispatcher to vehicles, vehicles to dispatcher, and one simplex channel for emergencies. These frequencies are distinct from those used by Boston and all the other 51 towns and cities within the MDC radius of operation. Intercommunication with units of these other departments and the State Police has been a problem on combined operations, such as the anti-war riots of the past few years. The MDC base transmitter is located on Blue Hill in Milton and has a power of 300 watts. Several repeaters help to provide the necessary coverage, although there are some dead spots (see last paragraph below). Mobile radios are 100-watt GE Master units with public address speakers and electronic siren. These cost about $1,300 for the basic radio, plus $100 for the electronic siren and an ignition blanker.

Captain Tobin mentioned the following points:

- Hard copy would be very desirable for management purposes and receipt of messages in out-of-car situations. A printer would be quieter than a blaring speaker, also confusion and lost messages should be minimized. A keyboard in the vehicle would eliminate much voice reporting.
- The MDC makes good use of its NCIC terminals, but system reliability has been a problem. He said down times of up to two hours had been experienced when no NCIC contact was possible, which raises problems when one has come to depend on it.
- He felt that radio security was very desirable, particularly in connection with drug raids or crimes in progress, but said that scramblers were too costly for general use in the MDC.
- The present MDC channels are not very congested for the message load under the present shared dispatching arrangement. However, the necessary relaying of messages between the stations and the dispatch center does cause delays (and errors on occasion). He would rather have his own transmitter to talk directly with his own vehicles.

Sometime after this visit with Captain Tobin, a further discussion was held with Officer James Powers, the MDC radio man. He said that there were some dead spots due to shadowing (areas perhaps 400-500 yards in diameter). The blankers in the mobile radios effectively eliminate ignition noise, and coded-tone squelch eliminates skip interference from distant users of the same frequencies. The worst problem as far as he was concerned was hum on the telephone lines used to connect the dispatch center with the transmitter.

3. Cambridge Police Department

On December 7, 1971, Messrs. Ward and Kelly visited the Cambridge Police Department, representative of a medium-sized city (pop. 100,000) that is part of a larger metropolitan area. The initial series of discussions were with Detective Lt. George Powers, who provided a good deal of information on general operations. He then introduced a dispatcher (Joseph Gould) who discussed the detailed operation of the radio room. Both of them felt that they were getting along pretty well with voice communications (both mobiles and a fair number of portables), and had not thought much about digital techniques. Also, they use their LEAP terminal (to the State Police computer, and through it to the NCIC computer) to the extent that they assign a full-time operator on this terminal to handle inquiries for the two radio dispatchers, plus other input/output not directly related to dispatch. They feel that this on-line service is invaluable, and miss it severely when the system is down for maintenance or other causes--often for several hours at a time.

The Cambridge Police Department has 250 men and 27 vehicles, ten of which are patrol cars: six two-man and four one-man. The usual vehicle strength on the street is six patrol cars plus a radar traffic car. City area is 6.2 square miles (2 by 3 miles), divided into four sections, each under a sergeant. A good deal of patrol is by foot, and most patrolmen carry portables.

The department has 35 UHF portables (about $1,000 each) which receive on the two 450-MHz-band dispatch frequencies transmit one channel higher. In addition, there are 10 high-band (154-MHz) portables that are used by the Tactical Squad on special operations. Tactical displatch uses the Cambridge Fire Department transmitter, and these portables are kept at the Inman Square Fire Station.

Lt. Powers mentioned several interesting statistics. They estimate that 2,000-3,000 people regularly monitor the Cambridge Police radio, and message security can therefore be a problem in certain situations. He also mentioned that Cambridge is a good place to get your car stolen--there were 3,300 cars stolen in 1971.

Dispatcher Joseph Gould (35 years with the Department) provided more details of radio operations. He estimated average radio activity at 75-80 contacts per 8-hour shift, or about 10 per hour. The LEAPS terminal operator is right in the dispatch room, and we observed one patrol-originated query on an auto registration number being checked at both LEAPS and NCIC. Total elapsed time to return the report (in this case negative) back to the patrol was less than one minute.

Cambridge uses two repeaters on tall buildings at each end of the city to improve coverage of its two 460-MHz channels. Separate R/T equipment is used for the inter-city network, which links police and fire departments in 29 surrounding cities and towns, plus the State Department of Public Works, on a common frequency (for some reason the directly adjacent city of Somerville is not on this network and must be contacted by phone). Finally, it was mentioned that all phone and radio calls are taped recorded and saved for three weeks; also all call slips are saved. The special telephone switching equipment setup in the dispatch room that is part of this recording operation is quite antiquated and becoming hard to maintain. Mr. Gould said that he wasn't sure what they would do if it really broke down.

4. Lexington Police Department

Lexington, Mass., is an independent, affluent, suburban community (pop. 35,000, about 5 by 6 miles in size) that is part of the Greater Boston urban area. Messrs. Ward and Kelly met with Chief James Corr on

December 7, 1971 and found that in Chief Corr's words, "we have no communications problems with our present voice setup", and "we are watching digital developments, but see no need for it in our operations at this time". It was evident that what he said was true. They have an almost clear channel (and tone squelch to eliminate hearing the one other channel user), all equipment is modern, there is a complete backup base station transmitter at the police station with emergency power, and radio coverage is such that vehicle-to-vehicle communications are possible between almost any two points in town.

It was of interest that in only eleven months since acquiring their LEAP-NCIC terminal, they had logged over 11,000 interactions, an average of about 32 per day (about one/day/1,000 population). Echoing the Cambridge and MDC comments, Captain Corr said that this system had become so much a part of their operation that any system down time was a problem to them.

Lexington operates simplex on high-band (155 MHz). The base transmitter is 300 watts and is located on a water tower on a high hill near the center of town. The mobile transceivers are modern solid-state, 65-watt units ($1,400 each), and high-gain antennas are used. Reliable base/mobile range is 15-20 miles, well beyond the town borders. The department has 45 men, and usually has 7-8 vehicles on the street at a time on roving patrol or radar traffic duty. Lexington also has a separate R/T for the 29-city intercity network. Chief Corr estimates that there are hundreds of eavesdroppers on the dispatch channel and would like to have a secure system, however, they have no plans to acquire scramblers. He also feels mobile extenders would be a good idea. Only a few men are on foot patrol or assigned traffic duty, mostly in the town center just a block or two from the station. These men carry portables.

Chief Corr stressed the fact that lack of good communications is disastrous to department operations and morale, and that he had thus pushed hard to obtain their present modern equipment and clear channel. He feels that communications problems in most small or medium-sized cities and towns result from a lack of money for modern equipment, not a lack of equipment technology, and that it is therefore necessary for police departments to emphasize to their town governments the need for reliable communications under all conditions, and maintain a continuing survey of matching funds or other aid that may be available. He said for example that Lexington had acquired some of its base station equipment with the help of Civil Defense matching funds.

APPENDIX E

GLOSSARY OF TERMS

This glossary covers some of the more important terms used in this report. It is not intended to be complete or definitive.

FSK	Frequency shift keying (frequency corresponds directly to binary value)
PSK	Phase shift keying (phase corresponds directly to binary value)
DPSK	Differential PSK (phase shift from previous bit corresponds to value of present bit)
AM	Amplitude modulation
FM	Frequency modulation
PM	Phase modulation
SSB	Single-sideband modulation (one sideband is entirely suppressed)
VSB	Vestigal-sideband modulation (one sideband is partly suppressed)
Modulation index	In FM, the ratio of the maximum frequency deviation to the modulation frequency
Submodulation	Digital modulation of an audio carrier (perhaps by FSK) which is then used to modulate the radio carrier by AM, FM, etc.
Direct carrier modulation	Digital modulation in which no subcarrier is used and the phase, frequency, or amplitude of the radio carrier corresponds directly or differentially to the binary value.
Shadow fading	Decrease in received signal amplitude in an area due to intervening terrain or structures.
Multipath fading	Changes in received signal amplitude as a function of position, caused by summation of a number of reflections of the signal which arrive at the receiver with different time delays.

Rayleigh fading	Multipath fading which can be modeled by the Rayleigh Probability Distribution
Free-space loss	Signal attenuation which varies as the square of the distance between transmitter and receiver
Excess-path loss	Attenuation of the mean received signal level over and above free-space loss due to multipath and shadow effects.
Error rate	Usually defined as the number of errors per bit transmitted, i.e., one error in 100,000 bits would be a rate of 10^{-5}
Error-detection coding	The addition of extra (redundant) data bits to a digital message which permit detection of transmission errors.
Error-correcting coding	Same as above, except the coding redundancy is such that errors up to a given level can be automatically corrected.
Parity coding (or check)	The simplest form of error-detection coding, based on whether the number of binary "ONES" in a given size data group is odd or even (usually used for each character code, but may also be used in block checking -- see below)
Block coding (or check)	Checking over a group of characters (perhaps an entire message)
Cyclic code (or coding)	A particular form of block-check code with simple implementation but powerful error detection capability
Polling	The process of sequentially addressing mobile units to permit them to transmit one at a time on a non-interfering basis.

BIBLIOGRAPHY

1. W. R. Young, Jr. and L.Y. Lacy, "Echoes in Transmission at 450 Megacycles from Land-to-Car Radio Units," Proc. IRE, Vol. 38, pp. 255-258, March 1950.

2. Anon, "Public Urban Locator Service (PULSE)", Institute of Public Administration and Technikron, Inc., Clearinghouse for Federal Scientific and Technical Information, October, 1968.

3. G. L. Turin, F. D. Clapp, T. L. Johnston, S. B. Fine, and D. Lavry, "A Statistical Model of Urban Multipath Propagation," IEEE Trans. on Vehicular Technology, Vol. VT-21, No. 1, pp. 1-8, February, 1972.

4. Lord John Rayleigh, "On the Resultant of a Large Number of Vibrations of the Same Pitch and of Arbitrary Phase," Philosophy Magazine, Vol. 10, p. 73, 1880.

5. M. Slack, "Probability Densities of Sinusoidal Oscillations Combined in Random Phase," Proc. IEEE, Vol. 93, Part III, pp. 76-86, 1946.

6. A. W. Drake, Fundamental of Applied Probability Theory, McGraw Hill, New York, 1967.

7. R. D. Leland and J. R. Smith, "Detroit Teleprinter Tests," Communications, April, 1969, pp. 17-24.

8. W. C. Jakes, Jr. and D.O. Reudink, "Comparison of Mobile Radio Transmission at UHF and X Band," IEEE Trans. on Vehicular Technology, p. 10, October, 1967.

9. H. W. Nylund, "Characteristics of Small-Area Signal Fading on Mobile Circuits in the 150 MHz Band," IEEE Trans. on Vehicular Technology, p. 24, October, 1968.

10. Mischa Schwartz, William R. Bennett, and Seymour Stein, Communication Systems and Techniques, McGraw-Hill, New York, 1966.

11. K. A. Norton, L. E. Vogler, W. V. Mansfield, and P. J. Short, "The Probability Distribution of the Amplitude of a Constant Vector Plus a Rayleigh-Distributed Vector," Proc. IRE, Vol. 43, pp. 1354-1361, October, 1955.

12. P. Mertz, "A Model of Impulsive Noise for Data Transmission," IRE Trans. on Communication Systems, Vol. CS-9, pp. 130-137, June, 1961.

13. A. D. Spaulding, "The Characteristics of Atmospheric Radio Noise and Its Effect on Digital Communication Systems," IEEE International Communication Conference, Philadelphia, 1966.

14. E. J. Bruckert and J. H. Sangster, "The Effects of Fading and Impulsive Noise on Digital Transmission Over a Land Mobile Radio Channel," *IEEE Vehicular Technology Conference Record*, pp. 14-16, December, 1969.

15. A. D. Spaulding, "Determination of Error Rates for Narrow-Band Communication of Binary-Coded Messages in Atmospheric Radio Noise," *Proc. IEEE*, Vol. 52, No. 2, pp. 220-221, February, 1964.

16. A. M. Conda, "The Effect of Atmospheric Noise on the Probability Error for an NCFSK System," *IEEE Trans. on Communication Technology*, Vol. COM-13, No. 3, pp. 280-284, September, 1965.

17. J. H. Halton and A.D. Spaulding, "Error Rates in Differentially Coherent Phase Systems in Non-Gaussian Noise," *IEEE Trans. on Communication Technology*, Vol. COM-14, No. 5, pp. 594-600, October, 1966.

18. G. F. Montgomery, "A Comparison of Amplitude and Angle Modulation for Narrowband Communication of Binary Coded Messages in Fluctuation Noise," *Proc. IRE*, Vol. 2, pp. 447-454, February, 1954.

19. Conda (see Ref. 16).

20. Halton (see Ref. 17).

21. E. N. Skomal, "Distribution and Frequency Dependence of Unintentionally Generated Manmade VHF/UHF Noise in Metropolitan Areas," *IEEE Trans. on Electromagnetic Compatibility*, pp. 269-276, September, 1965.

22. C. T. McCoy, Chapter 5 of *Vehicle Communications for a Dial-a-Ride System*, Report USL TR-70-15, M.I.T. Electronic Systems Laboratory, March 1971.

23. R. O. Schildknecht, "Ignition Interference to UHF Communication Systems," *IRE Trans. on Radio Frequency Interference*, pp. 63-66, October, 1962.

24. Society of Automotive Engineers, "Measurement of Electromagnetic Radiation from Motor Vehicles (20-1000 MHz), SAE J55/a," revised August, 1968.

25. Institute of Electrical and Electronic Engineers, "Measurement of Radio Noise, Generated by Motor Vehicles, and Affecting Communications Receivers in the Frequency Range 25 to 1000 Mc/s, IEEE Standard No. 263," November, 1965.

26. J. Martin, *Future Developments in Telecommunications*, 1971.

27. L. S. Kolsky, "Land Mobile, FCC, and Spectrum Allocations," *APCO Bulletin*, p. 20, August, 1971.

28. T. I. Dayharsh, *et al*, "A Study of Land Mobile Spectrum Utilization," Stanford Research Institute, July, 1969.

29. Address before the National Association of Radio Telephone Systems, August 1971.

30. D. H. Hamsher, ed, Communication System Engineering Handbook, McGraw Hill, New York, 1967.

31. Boston Police Department, Private communication.

32. J. M. Wozencraft and I. M. Jacobs, Principles of Communication Engineering, Wiley, New York, 1967.

33. B. P. Lathi, Signals, Systems and Communication, Wiley, New York 1965.

34. W. C. Y. Lee, "Theoretical and Experimental Study of the Properties of the Signal from an Energy Density Mobile Radio Antenna", IEEE Trans. on Vehicular Technology, Vol. VT-16, pp. 25-32, October 1967.

35. W. C. Y. Lee, "Mutual Coupling Effects on Maximal-Ratio Diversity Combiners and Application to Mobile Radio", IEEE Trans. on Communication Technology, Vol. COM-18, pp. 779-791, December 1970.

36. A. J. Rustako, "Evaluation of a Mobile Radio Multiple Channel Diversity Receiver Using Predection Combining", IEEE Trans. on Vehicular Technology, Vol. VT-16, pp. 46-57, October 1967.

37. D. G. Brennan, "Linear Diversity Combining Techniques", Proc. IRE, Vol. 47, No. 6, pp. 1075-1102, June 1959.

38. F. Hill and G. Peterson, Introduction to Switching Theory and Logical Design, Wiley, New York, 1968, pp. 167-170.

39. R. G. Gallager, Information Theory and Reliable Communication, Wiley, New York, 1968.

40. Antenna manufacturer private communication.

41. Hamsher (Ref. 30), p. 17-23.

42. Hamsher (Ref. 30), p. 17-9.

43. Hamsher (Ref. 30), p. 17-13.

44. D. O. Reudink and D. M. Black, "Some Characteristics of Mobile Radio Propagation at 836 MHz in the Philadelphia Area", IEEE Trans. on Vehicular Technology, Vol. VT-21, No. 2, May 1972.

45. R. W. Johnson, "Field Tests of Mobile Redioteleprinter Communications", National Symposium on Law Enforcement Science and Technology, Vol. II, p. 155, 1968.

46. Krug, Knukel, Smith, "Milwaukee Teleprinter Tests," Communications, August 1969, pp. 32-35.

47. Ralph E. Taylor, ed, Radio Frequency Interference Handbook, NASA, Washington, D.C., 1971.

48. R. J. Matheson, "Instrumentation Problems Encountered Making Man-Made Electromagnetic Noise Measurements for Predicting Communication System Performance," IEEE Trans. on Electromagnetic Compatibility, Vol. EMC-12, pp. 151-158, November 1970.

U.S. GOVERNMENT PRINTING OFFICE : 1974 O—529-418