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Advanced Mobile Phone Service:

Voice and Data Transmission

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Use of the AMPS (Advanced Mobile Phone Service) microwave channel, operating in the 800- to 900-MHz band, creates unique problems in addition to those connected with conventional land communications. Because the channel characteristics are not fixed, they present design challenges and impairments that must be dealt with to protect mobile telephone users from experiencing excessive variabilities in voice transmission quality and in control and signaling reliability. This paper describes the radio transmission features of the AMPS system, emphasizing the processing and control techniques designed to deal with the dynamic nature of the mobile radio channel.

I. INTRODUCTION

Transmission of voice and digital control information over the AMPS microwave radio channel in the 800- to 900-MHz frequency range presents significantly different problems than those encountered in conventional land communication systems. Unlike wire-line systems, the channel characteristics are never fixed, but vary with movement of the vehicle and changes in its surroundings. These dynamics give rise to a formidable set of design challenges since the character of the radio channel can change dramatically during a single call as the vehicle moves through the service area and is "handed off" to successive cell sites. Although these channel variations will occur, the radio transmission parameters, and consequently the voice and data transmission functions, have been designed to prevent the user as much as possible from experiencing corresponding changes in voice quality and in control and signaling reliability.

This paper examines the relationship between the impairments produced by the channel and the characteristics of the transmitted waveform. In particular, a consideration of the constraints affecting the performance of processors for voice and data transmission will provide the rationale for design selections in these areas. A feature of the system is the use of syllabic companding in the voice processor to control the modulation process in the presence of speech variability and also to enable the system to operate effectively in the presence of channel impairments. The technique chosen to transmit signaling data between the cell sites and the mobiles is described in detail. This technique incorporates a self-clocked modulating waveform and contains considerable redundancy to ensure reliable transmission over the mobile telephone channel.

Section II begins with a description of the radio channel. This channel is highly variable—no single set of rules covers all cases—and no attempt is made to qualify every statement with exceptions. However, the main features of the environment at 850 MHz that affect the design are presented, and impairments relevant to the cellular radio environment are outlined.

Baseband performance specifically related to mobile radio is discussed in Section III, along with the modulation methods and signal processing used in the system. Finally, Sections IV and V present an overview of the voice and data transmission methods chosen for AMPS.

II. THE AMPS MICROWAVE CHANNEL

2.1 Multipath propagation

Measurements[1–6] made by Bell Laboratories in Philadelphia, New York City, Whippany and Newark, N. J., and by others elsewhere confirm that a moving vehicle in an urban environment seldom has a direct line-of-sight path to the land transmitter. The propagation path contains many obstacles in the form of buildings and other structures, hills, and also other vehicles. Because there is no unique propagation path between transmitter and receiver, the instantaneous field strength at the mobile and base receivers exhibits a highly variable structure. The measurements show that the main propagation features in the radio environment are (*i*) multipath due to scatter or reflections from buildings and other obstructions most often within a few hundred feet of the vehicle, and (*ii*) shadowing of the direct line-of-sight path by intervening features of the terrain.

The received signal at the mobile is the net result of many waves that arrive via multiple paths formed by diffraction and scattering. The amplitude, phase, and angle of arrival of these waves are random, and the short-term statistics of the resultant signal envelope fluctuations over local geographic areas approximate a Rayleigh distribution.

Figure 1 shows a typical envelope of the received signal at a moving antenna measured along a short distance of travel. The so-called Rayleigh signal fades occur approximately one-half wavelength apart because of plane wave interference.[2] At carrier frequencies near 850

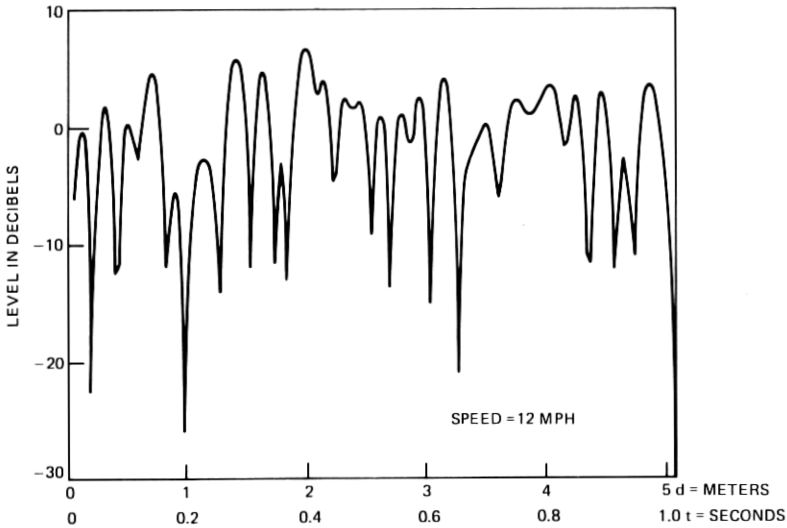

Fig. 1—Sample of Rayleigh envelope (carrier frequency 850 MHz).

MHz, independent fades are about 7 inches apart. As the mobile receiver moves through the radio interference pattern, it is therefore subjected to frequent fades. By reciprocity, the base station receiver tuned to a different frequency experiences the same sort of fades, although not at exactly the same time. These Rayleigh fades place the most severe limits on the quality of voice and data transmission at UHF.

Signal envelope fades into noise and interference can cause severe degradation in voice and data transmission. Let us look in greater detail at the representation of the multipath fading pattern given in Fig. 1, starting with the amplitude distribution.

Figure 2 shows the probability distribution function of the received instantaneous signal power normalized to its mean value.[2] The statistics of the fades are such that 10 percent of the time the signal will be 10 dB below its local mean, 1 percent of the time 20 dB below the mean, etc., where mean is defined in the figure as the mean received signal power. The plot in Fig. 1 is in decibels below this mean. Since vehicle motion induces signal fades via the multipath interference pattern, both the fading rate and fade duration depend on vehicle velocity.[2,7] Figure 3 is a plot, with velocity a parameter, of the rate of level crossing downward through a given level relative to the local mean. At 850 MHz, the rate of crossing a level 10 dB below the local mean happens to be numerically equal to the vehicle speed in miles per hour. Thus, at 20 mph, there will be a fade crossing the −10 dB level an average of 20 times per second. Related to the crossing rate is the average time the fading signal spends below a given level, i.e the

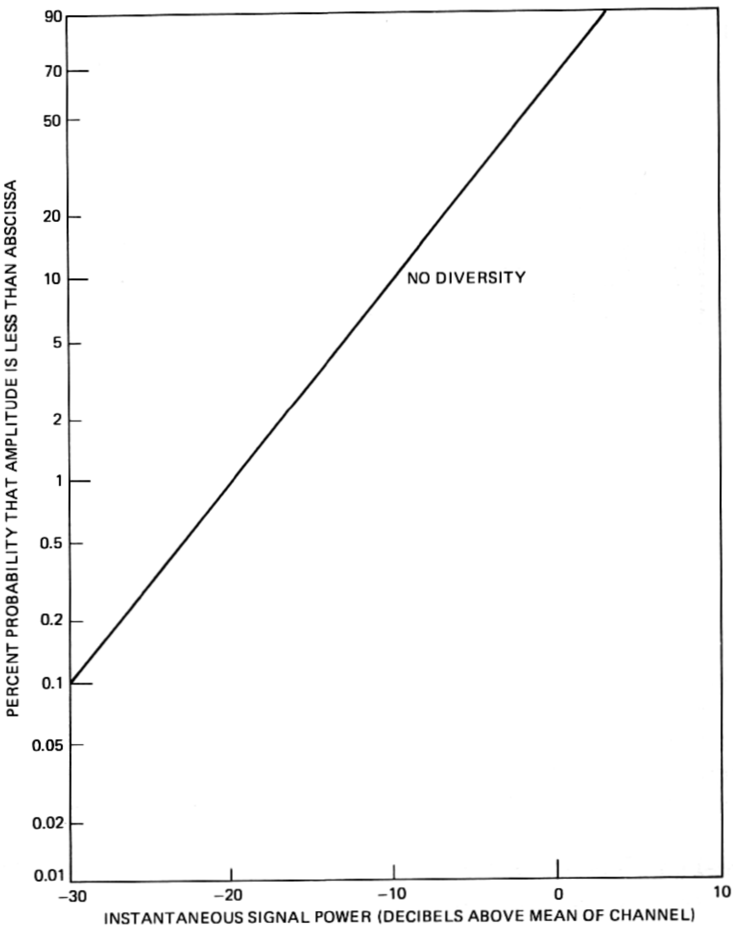

Fig. 2—Amplitude distribution function.

fade duration. The fade duration is inversely proportional to vehicle speed. At 20 mph, the average fade duration below −10 dB is 5 ms, as may be seen in Fig. 4.

In addition to the rapid Rayleigh fluctuations, there are also slower variations due to shadowing by local terrain features. Changes in the local mean-received signal power occur as the vehicle moves. The changes observed in local mean are slow only if compared to the Rayleigh fades, since 5-dB changes in mean signal level in less than 100 feet of vehicle travel are typical. A consistent result observed for these variations is that they have nearly a normal distribution for the received signal level measured in decibels—often referred to as a log-normal distribution. The variance of this log-normal distribution lies between 6 and 10 dB, with the larger variances generally found in heavily built-up urban areas.

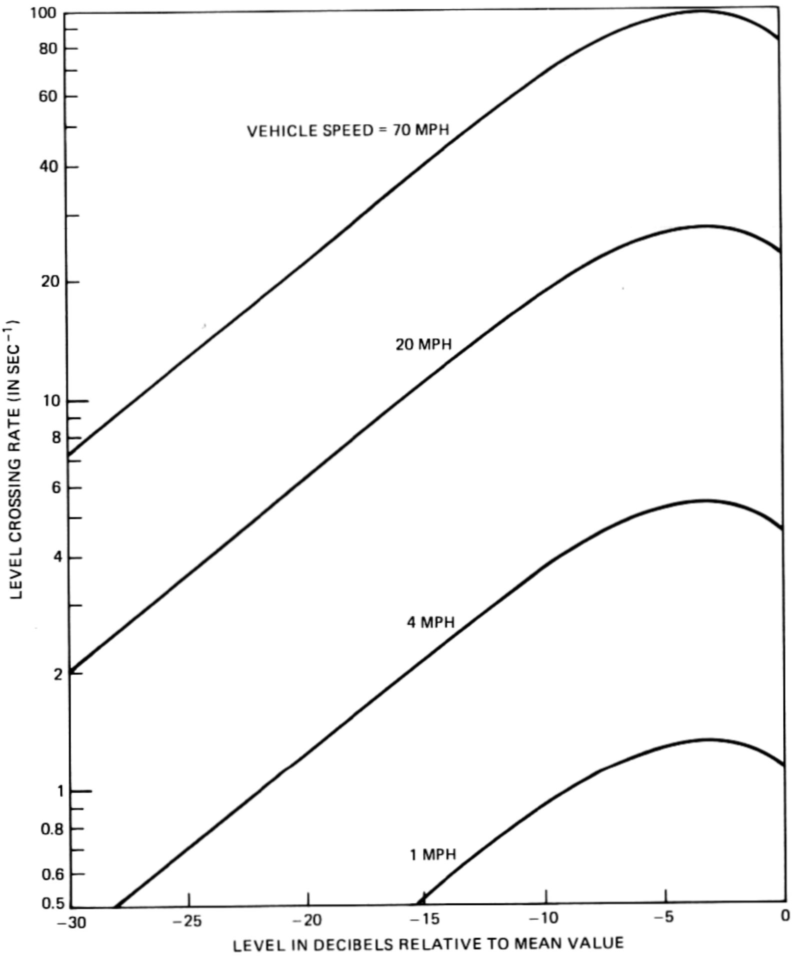

Fig. 3—Level crossing rate.

The delay distribution associated with multipath propagation has also been directly measured.[4,8] Since the resultant received signal is the superposition of signals which arrive via many paths, a spread in channel delay is observed. Measurements have shown that the received signals have a spread in delay which can be of the order of 3.5 microseconds in urban areas. The delay distortion which can result from this phenomenon provides limitations on the maximum signal bandwidth that can be transmitted over the channel. The delay spread-related coherence bandwidth[4,8,9] is defined as the bandwidth within which fading has a 0.9 or greater correlation. This bandwidth is usually >40 kHz in urban areas and >250 kHz in most surburban areas, so that frequency selective fading due to delay spread will not significantly

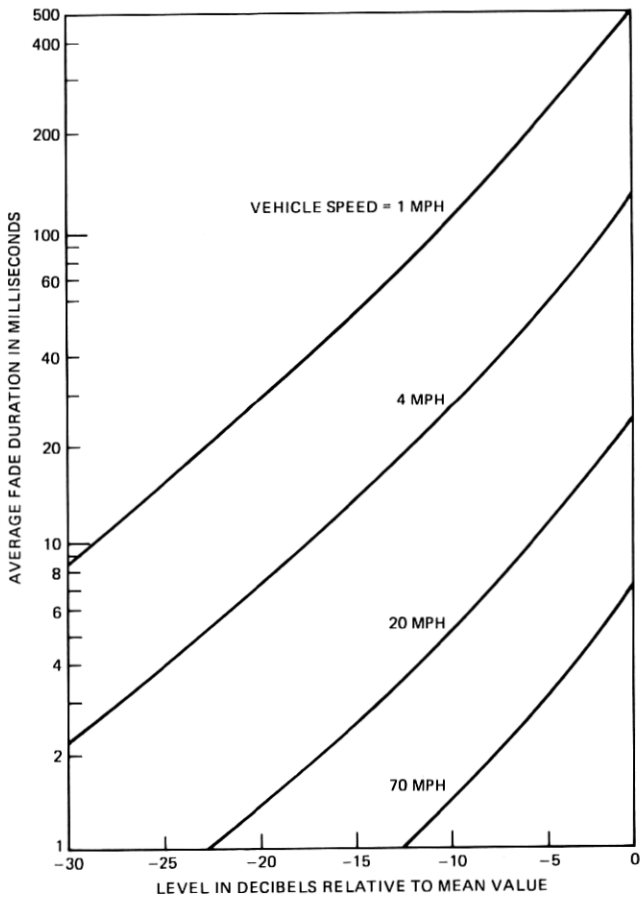

Fig. 4—Average fade duration.

impair transmission performance over the narrowband 30-kHz channels used in the AMPS system.

As the vehicle moves through the fading signal pattern, interruptions of voice modulation or losses of bits in data transmission occur when noise or interference captures the FM receiver during signal fades. The high rate of occurrence of deep fades, particularly those associated with multipath and shown in Fig. 1, provides the major source of transmission impairments in AMPS. While the use of linear modulation such as AM is conceptually possible, the rate of change and depth of fades that can occur at UHF have not permitted satisfactory transmission quality to be attained in this environment with those techniques. Frequency modulation—the approach used in AMPS—avoids the direct effect of these loss variations on information transmission. For this reason, frequency modulation has been selected for transmitting both speech and the binary data associated with system control functions, and it is in the context of FM with discriminator detection that transmission impairments will be discussed.

2.2 Impairments

The fading signal described in the preceding section will be received in the presence of various sources of impairments including receiver Gaussian noise, random FM, system-generated interference, and man-made environmental noise.

At high carrier-to-receiver thermal noise ratios, the FM receiver is "captured" by the signal, and the conversion to baseband produces a noise component with approximately a Gaussian probability density for the instantaneous voltage and the usual parabolic power spectrum characteristic of discriminator detection.[10] In addition to this "pseudo-Gaussian" noise is the so-called "click" noise[10] that results from capture of the receiver by noise. This impairment occurs with high probability if the instantaneous noise level exceeds the IF signal amplitude, as it often does near the bottom of signal fades. During these intervals, the phase of the composite IF waveform can change by 2π radians in a time period commensurate with the reciprocal of the IF bandwidth. This change causes the discriminator to present an impulse to the baseband processor, with the result that the click noise power spectrum is approximately flat in the voice bandwidth after the FM discriminator. Clicks furnish a major baseband noise component, and arrive in bursts which are time-correlated with RF signal fades.

The same multipath phenomenon that produces Rayleigh fading creates another impairment, referred to as random FM.[2] Random FM results from vehicle motion, and is due to time variation in the composite phase angle of the multipath signal at the antenna terminals. It provides an additional error component in the discriminator response. The power spectrum at baseband of random FM is a monotonically decreasing function of frequency (Fig. 5). Because of the waveform parameters and processing used in AMPS, random FM represents primarily a lower bound on baseband impairments for voice transmission when other noise and interference sources are removed. It is not a significant factor in AMPS data transmission.

The co-channel interference that results from channels reused in a mature small-cell system creates additional impairments. As discussed in Ref. 11, the system employs frequency reuse. More than one user can share the same channel frequency if they are far enough apart, but since their separation distance is finite, channel reuse generates a form of co-channel interference. The level and distribution of this interference depend on the frequency reuse pattern, and this has been balanced against system cost and performance objectives. Other factors include the implementation specifics, such as antenna height, directiv-

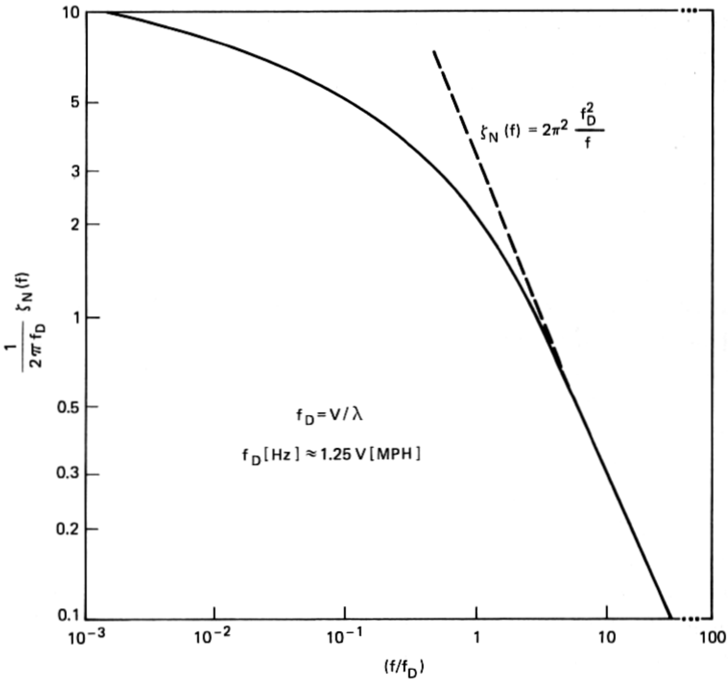

Fig. 5—Power spectrum of random FM.

ity, system handoff and control algorithms, siting requirements, and the channel assignment plan.

During the short-duration Rayleigh fades of the signal envelope caused by vehicle motion, the FM receiver can be captured by interference. The result is a burst of interfering voice modulation which is unintelligible because of the short duration of the fades (Fig. 4). In voice transmission, the relative amplitude of the baseband interference during the burst is dependent on the relative amplitudes of the instantaneous frequency deviation of the interfering and desired voice signals.

In addition, since the signal carrier and the co-channel-interferer carrier will usually be offset (because of oscillator tolerences) by a difference frequency that can fall within the receiver voice bandwidth, a detected difference frequency is sometimes audible as a "wobbling tone." For fading channels, this tone is audible at average carrier-to-interference ratios as high as 30 dB.

An associated side effect of co-channel interference, with offset-carriers, is the creation of additional click-line impairments that affect both voice and data transmission. The presence of a frequency offset increases the rate of occurrence of 2π phase steps due to carrier interference. The amplitude of the resulting interference clicks is generally less than those discussed earlier, since phase changes occur more slowly than those produced by receiver noise. The rate of phase change for the interference clicks depends primarily on the carrier offset frequency rather than on the IF bandwidth.

Environmental noise provides another source of potential impairment to AMPS transmission. Automotive ignition systems are major noise sources in this category, but others include neon lights, electrical machinery, and arc welding systems. In contrast with receiver Gaussian noise, environmental noise is often nonstationary and impulsive. The intensity of environmental noise is a strong function of local traffic conditions, and can vary from insignificance (many rural and suburban areas) to levels which can completely dominate other sources of noise and interference (intense urban "rush-hour" traffic).

Data have been collected in the central cell region of the Cellular Test Bed[12] in Newark, N.J. to characterize the "impulse" noise environment in a typical urban area. For example, Fig. 6 gives the probability distribution function of the peak power level referred to the antenna terminals (using a 28-kHz predetection filter) produced by impulse-noise in urban Newark. Data for this figure were obtained by first screening the data base to determine the maximum impulse noise level in each half-second data record, and then using these largest values to form the "bounding" distribution function of Fig. 6.

In the AMPS frequency band, the time-density of the impulses is relatively low, so that the ratio of peak to average power is very large.

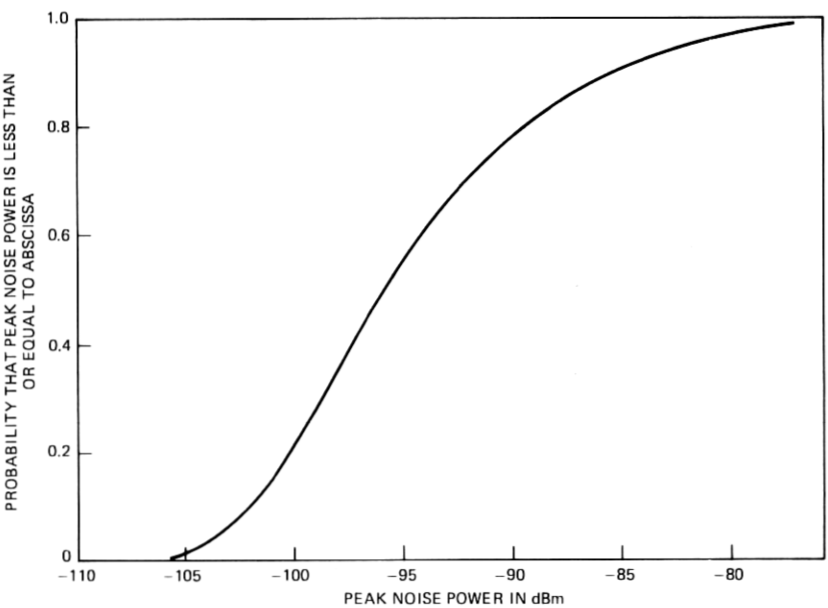

Fig. 6—Distribution function of impulse noise amplitude (848 MHz center frequency, 28 kHz bandwidth).

This is illustrated in Fig. 7, which contains two 1-second noise traces obtained from the Cellular Test Bed. The bottom trace contains post-IF filter noise data obtained by periodically sampling the composite receiver and impulse noise environment. The average noise power implied by this trace is about −120 dBm. The top trace contains only the largest value achieved by the composite noise process between successive points obtained for the bottom trace. For this example, the ratio of peak-to-average power is about 45 dB.

The non-Gaussian nature of this form of noise leads to baseband impairment characteristics different from those generated by receiver noise. The impairment tends to be a repetitive string of pulses, with pulse amplitude dependent on the relative amplitude of the "impulses" and RF signal, as well as the bandwidth and impulse response of the predetection filter. The baseband impairment power is proportional to the pulse rate. To place in perspective the relative importance of environmental noise and receiver Gaussian noise, current results indicate that environmental noise is primarily an urban consideration, and the impact on voice transmission will be more important than its effect on AMPS data transmission. The effect of environmental noise on signaling performance is low because the arrival rates of the noise impulses are low compared with the signaling data rates. Signaling is also aided in this respect by the redundancy used in data coding (Section V).

III. TRANSMISSION

In many FM systems, the capture of the receiver by the signal of interest at modest values (10 dB) of IF S/N or S/I ratio provides an important mechanism for enhancing baseband performance when RF impairments are present. The capture phenomenon is not as dramatic in suppressing impairments in the AMPS system as it is in broadcast nonvehicular FM systems because of the severity and rapidity of the signal fades on the mobile channel. These fades create transitory situations during which the RF signal no longer dominates noise or interference. The resulting loss of signal capture introduces impairments into the baseband response that can be orders of magnitude higher than those experienced with nonfading channels operating at the same average RF signal level. The severity of these impairments will not be uniform over the coverage region of AMPS, but will tend to follow the trends in signal and interference strength dictated by propagation considerations (path loss dependence and shadow fading).

The AMPS system employs both spatial diversity signal reception techniques and specialized designs for the voice and data transmission functions to prevent as much as possible the user from experiencing the effects of channel impairments.

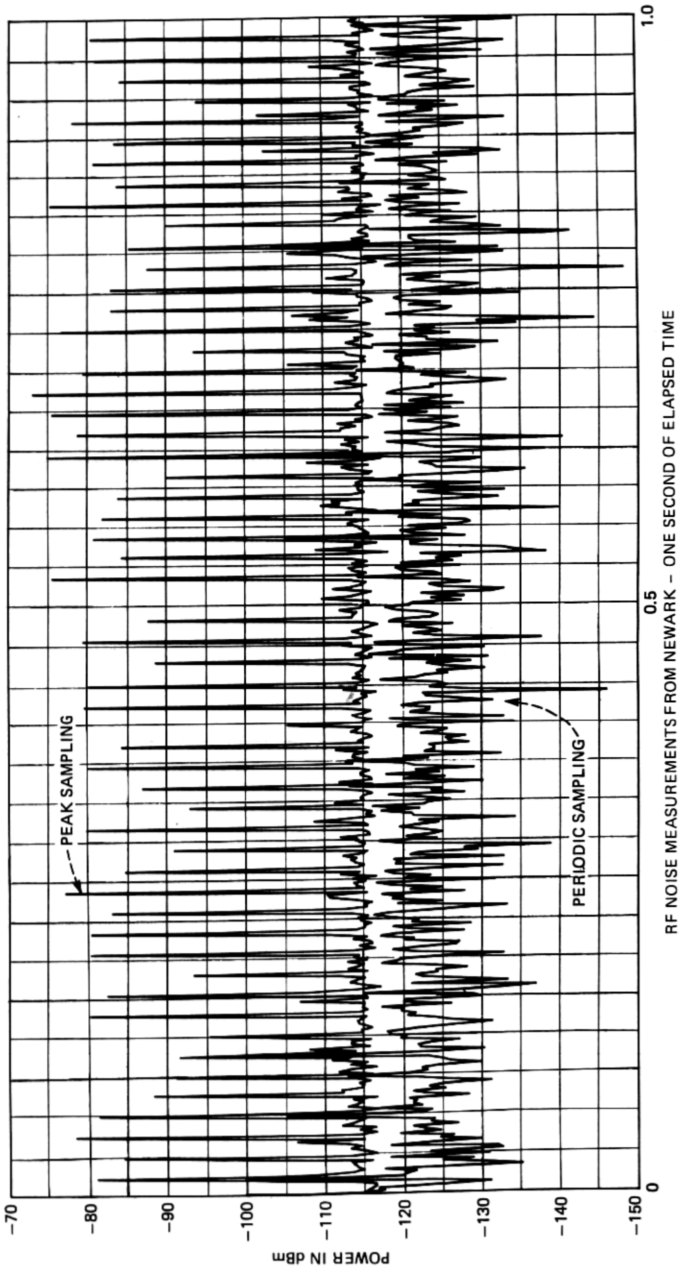

Fig. 7—Environmental noise trace.

3.1 Channel spacing

In the AMPS system, RF transmission channels are spaced by 30 kHz. This spacing is achieved by limiting to 12 kHz the peak-frequency deviation generated by modulating voice signals, and by applying an RF frequency assignment plan that does not permit the use of adjacent channels in the same cell.[11]

The frequency spacing of RF voice channels is an important system parameter, as it affects both performance and cost. The voice-channel spacing selected for AMPS reflects a consideration of each of these factors.

For practical reasons, the RF channels cannot be bandlimited prior to transmission from either the cell site or the mobile transmitter. Hence, the potential for transmission impairments that can result from adjacent channel interference is a major consideration.

The peak frequency deviation and baseband spectrum of the modulating signal determine the spectral occupancy of the radiated FM waveform. Adjacent channel interference resulting from "splatter" of this waveform into neighboring channels is influenced by the spacing of the RF channels, the adjacent channel response of the receiver predetection filter, and the geographic separation of adjacent voice channels.

Impairments resulting from adjacent channel interference can be reduced by increasing the frequency spacing of the voice channels. This approach, however, will also reduce the total number of RF channels available for use in the system. A reduction in the number of available channels increases the rate at which cell-splitting must occur in order that the user population be served without excessive facility-blocking. Thus, on the average, fewer users will be served by each cell-site, and an increase in costs will result.

The performance factors related to channel spacing have been investigated in the laboratory by using a Rayleigh Channel Simulator[13] to test transmission in the various impairment environments. Laboratory data were used to quantify performance sensitivities and tradeoffs. The impairment environments included Gaussian receiver noise, man-made impulse noise, co-channel and adjacent channel interference, random FM, and frequency synthesizer noise. In addition, field data from the Cellular Test Bed have been used to corroborate the laboratory models and results obtained with them.

The results of these tests and also the results of cost-analysis studies were used to establish the channel spacing and waveform parameters that are used in AMPS.

3.2 Diversity

The high rate of occurrence of deep fades, particularly those associated with multipath and represented in Fig. 1, can be reduced by the use of spatial diversity.[2] One class of systems using spatial diversity employs signals from two or more antennas that are co-phased and added prior to detection (equal-gain or "Granlund" diversity). Alternatively, the antenna which gives the highest S/N ratio could be selected for signal reception (selection diversity), or outputs of multiple antennas could be switched to a single receiver using a control algorithm that is driven by the detection of signal fades (switched diversity). Spatial diversity can significantly improve transmission performance because of the small probability that all antennas, if spaced a half wavelength or more apart, will simultaneously experience a signal fade. As an illustration, the distribution function for the composite envelope resulting from two-branch, equal-gain, diversity combining is compared with that of a single branch receiver in Fig. 8. With two branches,

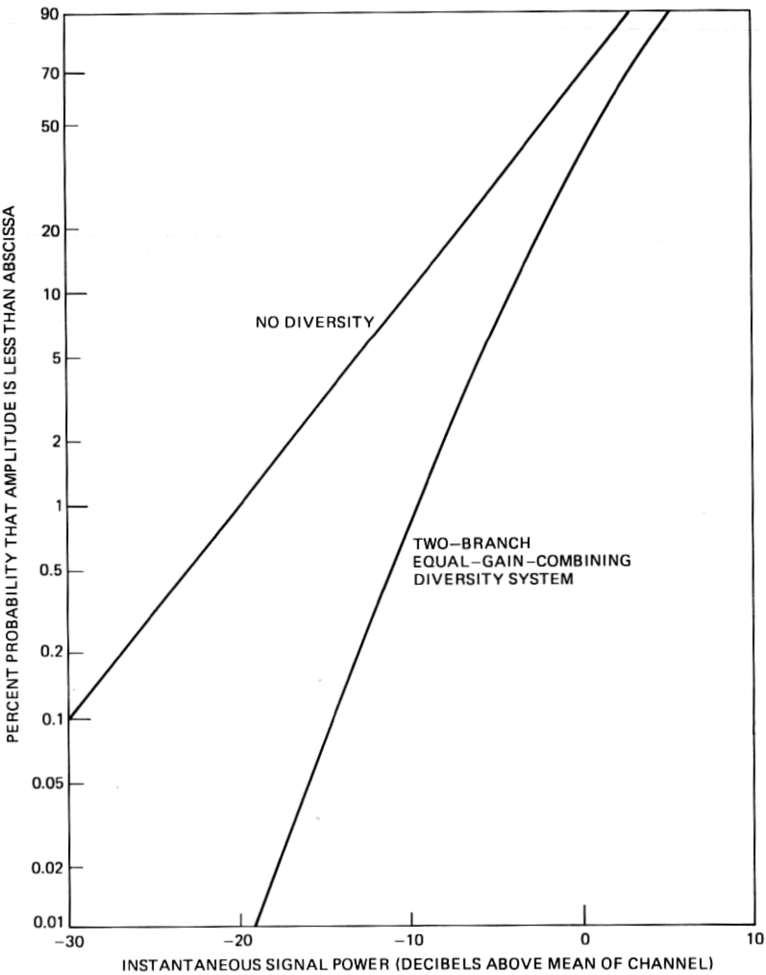

Fig. 8—Amplitude distribution functions.

the probability of fades 10 dB below the mean signal strength decreases to 0.8 percent from the 10-percent probability obtained without diversity. At 18-dB average carrier-to-receiver noise ratio, the resulting improvement in voiceband S/N ratio is about 12 dB.

This substantial improvement is not obtained without cost, however. Equal-gain and selection diversity each require simultaneous dual-channel reception for each diversity branch, including separate antennas and RF units, IF strips, etc., up to the point of the diversity combination. "Switched" diversity requires less duplication of equipment, so it costs less than the others, but it also does not work as well.[2] In AMPS, current plans are to use equal-gain or selection diversity at the cell sites, where the cost is shared by many users, and to use "switched" diversity in the mobile units.

IV. VOICE PROCESSING

4.1 Considerations

Control of the system RF characteristics, which affect the level of noise and interference impairments in the detected voiceband signal, involves considerations such as effective radiated power, cell radius, and the frequency reuse factor.[11] Since practical considerations restrict the flexibility of this type of control, other techniques, in addition to receiver diversity, have been investigated. In AMPS, speech signal processing has provided a relatively economical degree of freedom for substantially improving the quality of service.

In addition to RF considerations discussed earlier, studies[14] have shown that considerable variability exists in talker volumes and in the corresponding amplitude of electrical signals generated by different talkers using telephone microphones. The average signal power at baseband in the FM receiver is proportional to the mean-squared frequency deviation, $f^2_{\rm rms}$, produced in the transmitter modulator. To maximize performance in the presence of impairments, it is important that $f^2_{\rm rms}$ be controlled. In AMPS, the rms frequency deviation for the "nomimal" talker is set at 2 kHz.

Previous studies[14] suggest that, in the absence of some type of modulation control, talker and microphone variability will result in a log-normal distribution for $f^2_{\rm rms}$, with a standard deviation of about 5 dB. Speech from "weak" talkers will suffer a degradation in receiver-voiceband, signal-to-impairment ratio directly proportional to the reduction in $f^2_{\rm rms}$. This reduction directly affects perceived transmission quality, producing a commensurate reduction in the subjective rating of channel quality. At the opposite extreme, speech from "loud" talkers is impaired through excessive "clipping" distortion in the transmitter. (Amplitude clipping is used in the transmit processor to limit the peak-instantaneous frequency-deviation associated with the transmitted waveform so that adjacent-channel interference effects can be controlled.) The baseband processing selected for AMPS provides a means of reducing the effect of variability in volume levels on impairment and distortion performance.

4.2 Description

Figure 9 is a block diagram of the voice processing circuitry. The use of filtering and amplitude limiting in the transmit processor, to control spectrum splatter into adjacent channels (and filtering in the receiver to control the effects of noise), follows typical design procedures for FM systems. The use of differentiator pre-emphasis and integrator de-emphasis to improve performance in the presence of channel impairments is also consistent with standard design approaches. A difference in this application is that, instead of suppressing noise relative to speech as in most FM systems (where the noise characteristics are different from those of the AMPS), de-emphasis here primarily shapes the spectrum of the major noise component (the "clicks") so that it is similar to, and generally subjectively masked by, the presence of speech.[15]

The compandor has been found to provide important improvements in AMPS voice transmission quality. It controls the effect of speech level variability on clipping distortion and frequency deviation generated by the modulator, and also improves the subjective quality of the channel when it is operating in the presence of impairments.

Compandors have been used in wire-line telephone circuits to improve performance over relatively noisy paths and also to reduce crosstalk problems. Their use in AM radio systems has been previously considered, but uncertainties in the path loss between transmitter and receiver for various links have forced the use of special channels dedicated to providing control information for the receiver. For analog FM transmission, however, path loss variation (or its equivalent) is far less of a problem than for AM transmission. Thus, use of the compandor in the AMPS system does not require complex special control channels.

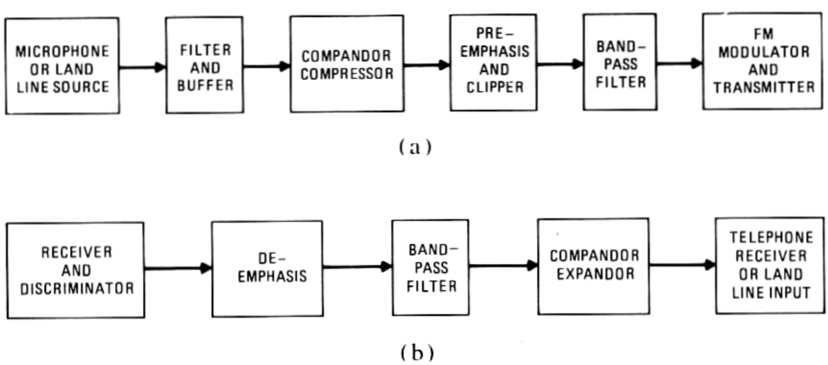

Fig. 9—AMPS audio processor. (a) Transmit processor. (b) Receive processor.

The syllabic compandor is made up of a matched compressor-expandor pair with carefully controlled time constants. Both are variable gain devices, with gain control as illustrated in Fig. 10 and nominal input-output characteristics as shown in Fig. 11. The signal-dependent "gain" of the compressor is matched by a complementary signal-dependent "loss" of the expandor so that speech may be transmitted without perceptible distortion and level changes. This matching is achieved by balancing and stabilizing the operating point of each of the devices, and insuring that each has the proper time constant for gain control.

The compandor in this application uses attack and recovery times[16,17] of 3 and 13.5 ms, respectively, which are the CCITT-recommended nominal values. Achieving these values requires smoothing the output of a half-wave rectifier with a low-pass filter having a 20-ms R-C time constant. Although the selected values for the attack and recovery times reflect a compromise between low-frequency distortion and intersyllabic noise-quieting,[17] they serve a dual purpose in mobile telephony. The compressor reduces, by the companding law, the variability in clipping distortion and rms frequency deviation associated with the distribution of speech volumes to which the system will be exposed. The most common companding law for wire-line systems is nominally 2:1, which provides a reduction in the output-level variation by a factor of 2 (in dB) over that of the compressor's input

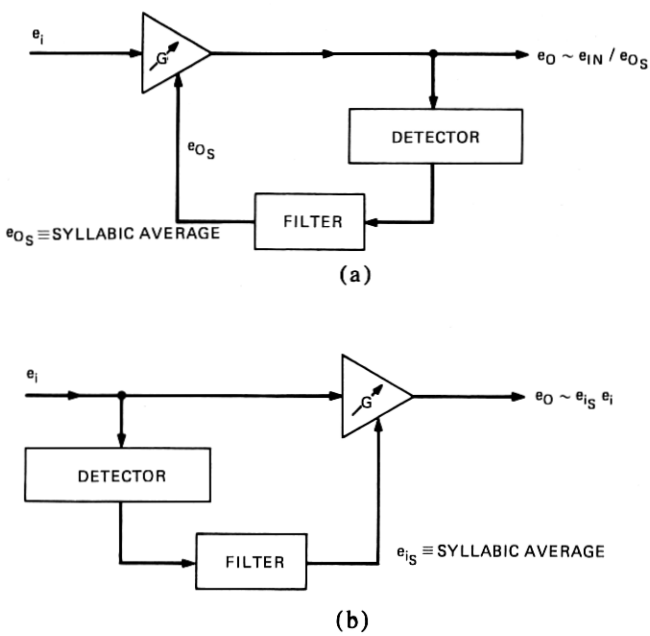

Fig. 10—Compandor operation. (a) 2:1 compressor. (b) 2:1 expandor.

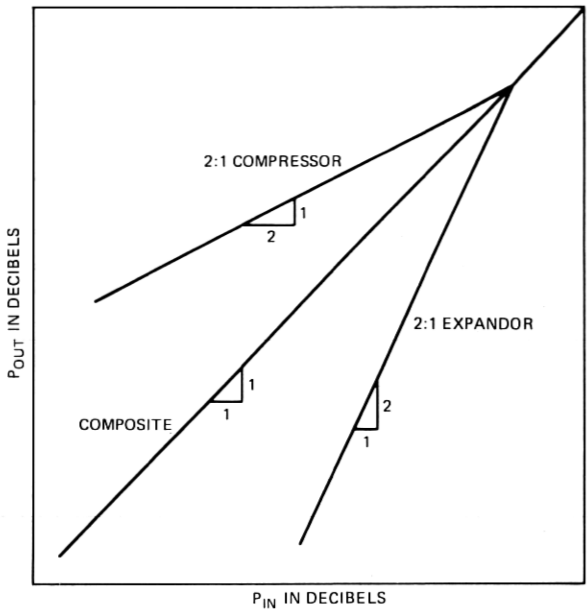

Fig. 11—Input/output characteristic of compandor.

waveform. The compressor's response time is sufficiently slow so that it does not respond to level changes that occur significantly faster than the 20-ms R-C time constant, but restricts primarily the slower syllabic variations. Hence, the compressor does not significantly affect the speech-crest factor and spectral content.

The bandpass filter which precedes the compressor serves to band-limit speech signals so that out-of-band speech energy does not influence the gain of the compressor or affect the inband loss of the amplitude limiter.

The receiver expandor not only removes transmitter predistortion created by the compandor compressor, but also suppresses receiver noise and interference relative to speech signals, thereby quieting the receiver. For low-level impairments whose average level varies slowly with respect to the expandor response time (such as random FM, Gaussian noise, and the co-channel carrier-offset "wobbling tone"), the expandor output signal-to-impairment ratio (in decibels) is improved by a factor that approaches the companding law. This is the typical quieting mechanism for wire-line systems.

The second way in which the audio impairments of mobile radio are suppressed is through the finite response time of the expandor. The expandor is normally in a high-loss state in the absence of an applied audio signal. Thermal noise clicks present in the receiver-audio-filter response may be larger in amplitude than levels corresponding to nominal talkers. However, individual clicks at the input to the audio receiver last only about 0.3 ms and lack sufficient energy in the loss control bandwidth to cause the expandor to change from its high-loss state fast enough to respond to them.[18] Since expandor-loss control is achieved through integration of the received baseband signal by means of a low-pass filter with a time constant of 20 ms, the expandor will not be fully driven from its high-loss state by burst of clicks or co-channel interference lasting less than about 20 ms. This inertia in the expandor response results from the CCITT attack-time standard, which is made large enough to prevent excessive voice distortion at low frequencies due to compandor action. For mobile telephone operation, this specification serves a dual purpose by inhibiting the expandor response to bursts of clicks and interference.

Because of the above attributes, the expandor is a very effective suppressor of radio impairments at the receiver, especially in the absence of voice-signal modulation. The quieting is also subjectively evident between syllables and during natural pauses in speech. In addition, noise that is dominated by short-term speech power tends to be masked by speech. This, in conjunction with receiver quieting during the absence of speech, enables the 2:1 compandor/de-emphasis combination to provide a very effective subjective improvement in transmission quality in the presence of radio impairments. The nature and severity of the channel impairments, as discussed, create an acute need for such improvements.

The use of a higher companding law, such as 4:1, to magnify the transmission control and quieting performance of the 2:1 compandor planned for the AMPS system was also considered. Increasing the companding law beyond 2:1 can introduce additional voice transmission impairments[15] because of the impact of the processing between the compressor and expandor on the overall net loss of the compandor. Power removed from the speech signal by filtering and amplitude limiting (necessary functions for noise and RF spectrum control) can introduce commensurate syllabic-level variations in the speech signal leaving the receive-audio processor because of the multiplicative effect of the compandor. Limiting the companding law to 2:1 effectively eliminates this distortion mechanism, while still offering most of the subjective performance benefits of higher companding laws when channel impairments are present.

V. DATA TRANSMISSION

5.1 Purpose

Mobile units in the AMPS system respond to orders received from the cell sites, which are in turn controlled via data links from a Mobile Telecommunications Switching Office (MTSO).[11,19] All phases of the mobile call, including call setup, handoff between cell sites, and call disconnect require data signaling over the radio channel. On this channel, there are two categories[20] of signaling messages—those sent within a continuous stream of bits and those sent as discontinuous bursts. In the first category are mobile pages, system status reports, and various overhead function messages incorporated within a continuous digital stream transmitted over dedicated "paging" channels from the cell site to the mobiles. The second category includes call release and cell-site handoff orders sent to the mobile on the voice channel, and requests sent to the cell site on the appropriate "access" channel by the mobile for access to the system.

The paging message for a mobile consists principally of the mobile telephone number of the vehicle being paged plus some overhead bits as described elsewhere in this issue.[20] To the 28 message bits required for a page, 12 additional bits are appended for parity protection, and the encoded message is transmitted at a 10-kb/s rate. An active mobile tunes to the strongest paging channel in its assigned set and monitors the messages received while awaiting its own telephone number. From these messages the mobile can derive instruction pertaining to system access and eventual voice channel assignments.

The transmission rate for mobile access transmissions to the cell site and handoff commands from the cell site to mobile is also 10 kb/s, but these messages are not sent as part of a continuous data stream. To obtain synchronization of the discontinuous message transmission at the mobile or cell site receiver, these transmissions have a synchronization prefix attached that uses an alternating 1010··· "dotting" sequence. This sequence, which is recognized as a 5-kHz tone, initializes the phase of a clock that is subsequently updated in a phase-locked loop. The message following the synchronization prefix consists of a burst of 10-kb/s data lasting approximately 100 ms. This message supplies the information necessary to accomplish the discontinuous signaling functions. For all data functions (continuous paging, discontinuous requests for service, handoff, and call disconnect), the messages are automatically repeated to provide five voting detections for each bit. The message repeats are stored and summed (majority voted) at the receiver.

5.2 Carrier modulation

All methods of digital transmission over radio channels are applicable to mobile radio. The method chosen for AMPS uses direct-binary frequency-shift-keying (FSK) of the carrier with discriminator detection. Binary data can be transmitted with FSK modulation up to a rate approximately equal to the IF bandwidth, but for any bit rate an optimum peak deviation exists that minimizes the bit error probability.

For AMPS, a biphase (Manchester), bit-encoding format was adopted. Each logic 1 is encoded as a 0, 1 and each logic 0 as a 1, 0, and the peak frequency deviation chosen to minimize the bit error probability on the fading channel is ±8 kHz for an RF predetection bandwidth of approximately 30 kHz. The envelope of the Manchester-encoded baseband spectrum for a random bit stream, and the resulting RF spectrum, are shown in Figs. 12 and 13. While this coding doubles the effective transmission rate, it does provide several advantages.

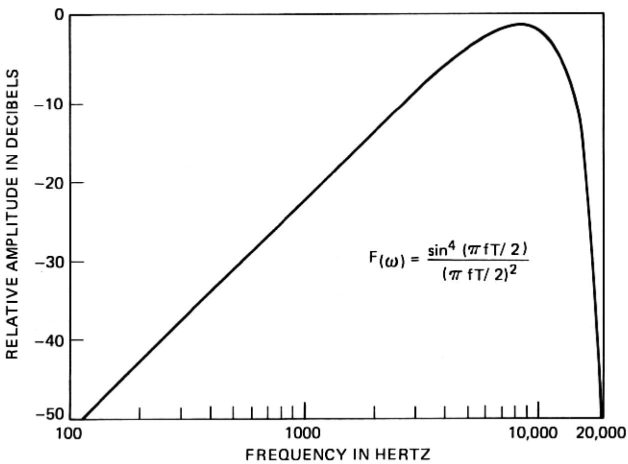

Fig. 12—Power spectrum of Manchester coded data (information rate = 10 kb/s).

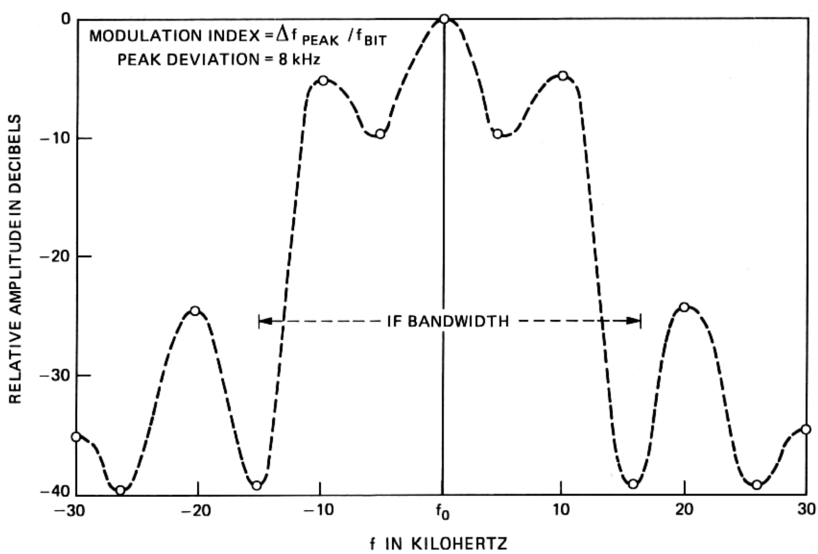

Fig. 13—RF spectrum of FSK signal.

Because of the biphase coding of the 10-kb/s data stream, the peak of the power spectrum for data transmission is well above the voice-band. This separation is an advantage in a system transmitting both voice and signaling data on the same channel. Synchronization of the receiver to the data stream is also aided by the ever-present biphase bit transitions which exist independently of the code transmission being sent. Furthermore, since the spectrum of biphase coding has no zero frequency component, the desired binary FM waveform can be implemented with a phase modulator preceded by an integrator. The maximum modulator phase shift required is the shift over one bit interval (±0.8 radian), which is within the capability of the phase modulator used for voice signals.

For data transmission as for voice, attention must be focused on the short-term signal-envelope variations (the Rayleigh fades), since for both modulation systems operating at carrier-to-noise or carrier-to-interference ratios of interest, the error performance is dominated by the fading character of the channel. The bit-error probability when the instantaneous carrier envelope is 15 dB above the noise level is, for noncoherent FSK, less than 10^{-7}. However, when the channel is subjected to Rayleigh fading at a 15-dB average carrier-to-noise ratio, the bit-error probability is approximately 3 percent. Thus, most errors occur during deep fades of the signal into noise or co-channel interference as the vehicle moves through the multipath interference pattern. These errors occur in dense bursts associated with the duration of individual signal fades. Furthermore, the bit-error probability is substantially independent of data rate until bit lengths approach the average fade duration. That is, integration over the bit interval cannot improve the error rate unless integration times are at least on the order of the average fade duration. Consequently, data rates should be either very low (200 Hz) or as high as the channel bandwidth allows. Time delay spread, which has no measurable effect on voice transmission, does affect the faster data modulation. The spread in time delay observed[4,8] results in an irreducible bit error rate for digital transmission that is independent of the noise level. This rate, which is of the order of 10^{-2} or less, is due to FM distortions at baseband created by the delayed echoes at the receiver input. The effect of these echoes on message error rate is negligible because of the large amount of redundancy employed in the system to cope with the more severe effects of signal envelope fades into noise and interference.

The bit-error rate is essentially one-half during fades into noise or interference, and error-burst frequency and duration are related to the speed-dependent fade interval and fade-duration distributions. Figure 14 shows the frequency of error bursts of a given length for a 15-dB average carrier-to-receiver noise ratio. The data shown in this figure were obtained at 20 mph, where the average duration of a fade 15 dB below the mean signal level is approximately 25 bits for a transmission rate of 10 kb/s. Error bursts of about 10 bits occur 10 times a second, a rate that is the average rate of occurrence of 15 dB fades at 20 mph. Note, however, that longer bursts of 50 bits or more occur every second. The reason for this is that fades below −15 dB have a high probability that they will be of long duration. That is, although the average fade duration of −15 dB fades is about 2.5 ms, durations five times this average are not at all unlikely. The error-burst distribution on a log plot (Fig. 14) is a straight line because the fade-width distribution (Fig. 15) follows an exponential law.

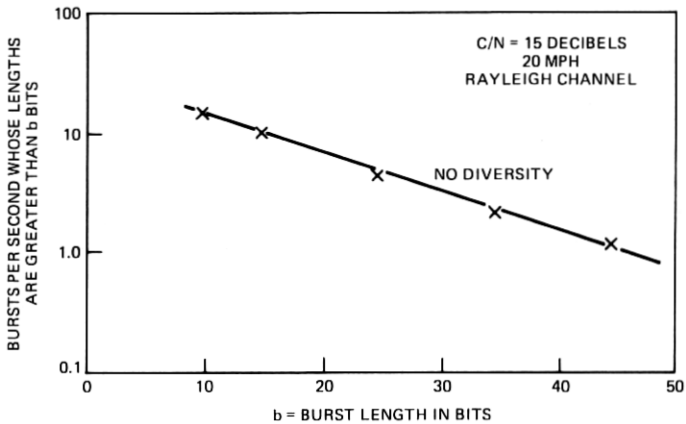

Fig. 14—Frequency of error bursts.

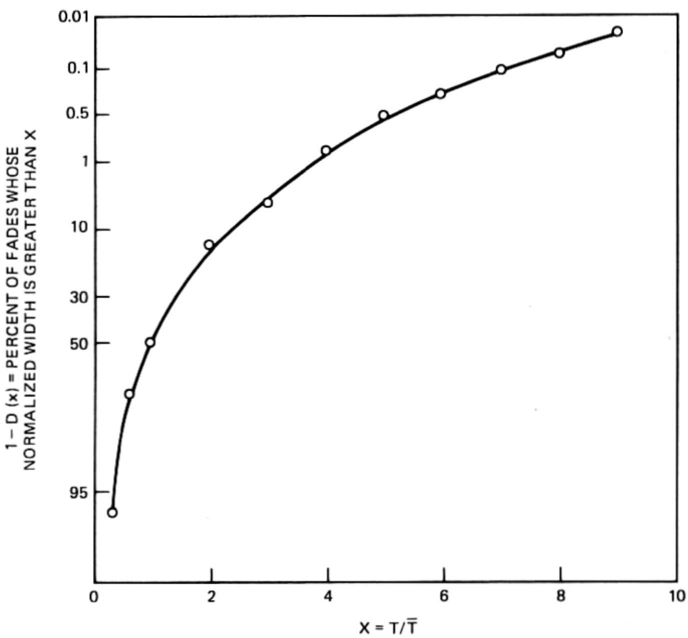

Fig. 15—Fade width distribution function.

5.3 Channel encoding

The virtual certainty that bits in long blocks will be lost for any practical mobile environment places constraints on the type of coding that can be used. Figure 16 illustrates why simple forward-error correction is not practical. To transmit 100 message bits in a fading channel with a message error rate of 2 percent at 15-dB average carrier-to-noise ratio requires a decoder capable of correcting 25 or more errors. One might consider massive interleaving of bits, which will reduce the number of message bits "trapped" by a given fade. Figure 17 shows the results of this on code detection performance. With a 50-bit spacing between each code bit (i.e., 50 words were interleaved to reduce error bursts), the error rate remaining after six error corrections in a 100-bit word is still approximately 5 percent. The effectiveness of bit interleaving in the mobile channel is limited by the high probability of long fades.

The radio channels do not lend themselves to a request for repeat and retransmission when an error is detected. Instead, each message is automatically repeated and the repeats summed to decrease the effective bit-error rate.

Each repetition is encoded with a cyclic redundancy check and the sum word is error-corrected. The usual trade-off is possible between the number of errors corrected and the number of errors detected. A single error correction on the summed message results in a performance comparable to the performance of land data links, and it has the advantage that implementation at the mobile is simple. For both the continuous paging function and the discontinuous functions of handoff on the land-to-mobile link, a 40-bit shortened BCH code (distance 5)

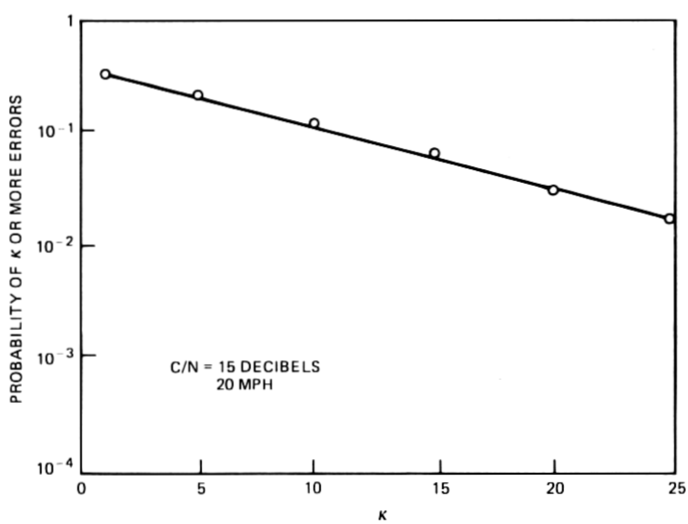

Fig. 16—Error rate distribution for single transmission of a 100-bit word.

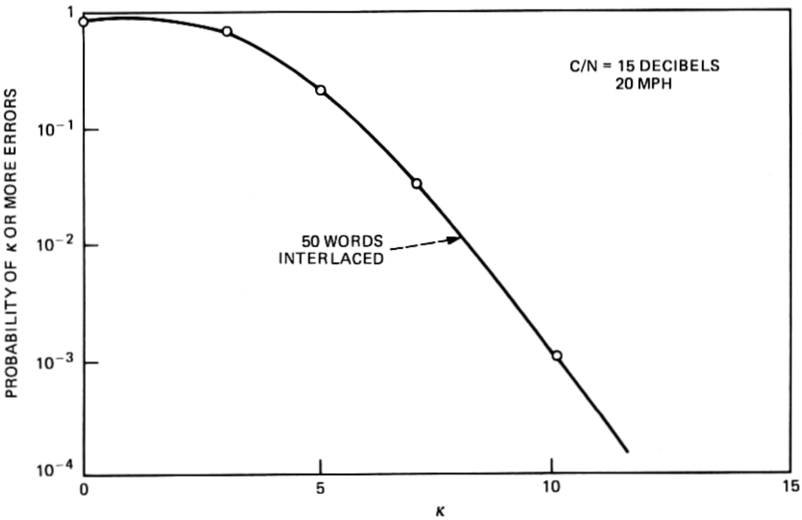

Fig. 17—Error rate distribution for a 100-bit word with bit interlace.

was chosen.[20] For the access and vertical services function on the mobile-to-land link, a 48-bit message using the same BCH code was chosen. Each message is given a total of five suitably spaced transmissions, and the five words are summed with bit-by-bit majority voting.* The one-error correction capability results in a word error rate of 2×10^{-3} at 15 dB. Because the probability is high that a given fade will create multiple errors, the spacing of the word-repeats is an important parameter related to the vehicle speed. For the data shown in Figs. 18 and 19, the spacing between corresponding bits in adjacent repetitions is 10 ms (or 100 bits), and is representative of the message formats of the AMPS system.

Message repetition with majority voting and single-error correction has proved to be a simple way to supply reliable signaling over the mobile telephone channel. The redundancy inherent in this approach and the self-clocking nature of the Manchester modulating waveform are the basis of the data transmission technique used to provide the signaling and control information essential to the operation of the system.

VI. CONCLUSION

The characteristics of the urban radio channel in the 800- to 900-MHz band have strongly influenced the design of the voice and data transmission systems in the AMPS system. The dynamic nature of the channel leads to extremely large fluctuations in the transmission

* The land-to-mobile discontinuous message is repeated 11 times, but only 5 of these repeats are loaded. The extra redundancy assures reception of the 5.

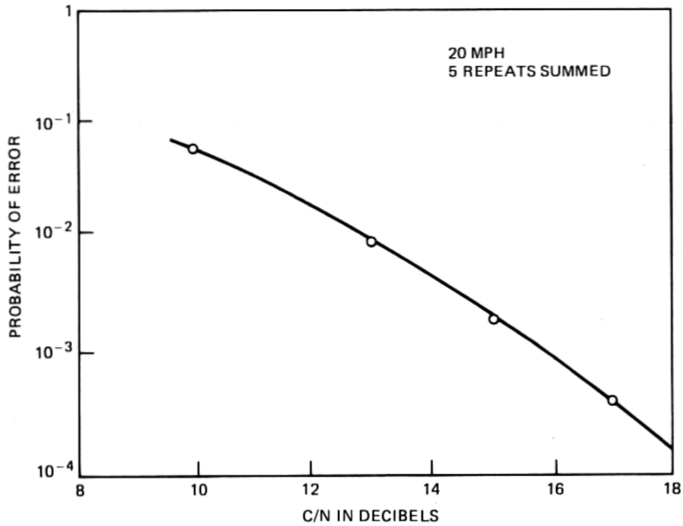

Fig. 18—Error rate for (40,28) code (carrier frequency 850 MHz).

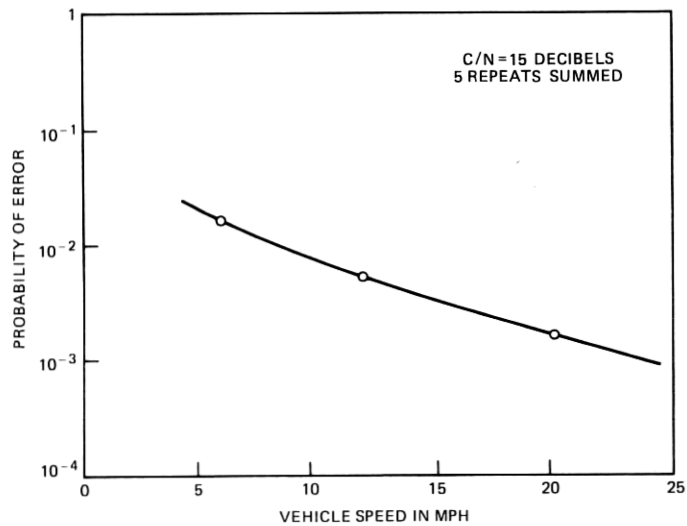

Fig. 19—Error rate vs vehicle speed for a (40,28) code.

environment not only from call to call, but also during individual calls. Since the potential impact of this variability is great, processing precautions have been taken in the AMPS system to prevent the user from experiencing corresponding variabilities in voice transmission quality and control reliability. The techniques themselves have undergone extensive testing, both in a controlled laboratory environment in which the radio channel is simulated and also in an experimental cell site at Whippany, N. J. Testing has also been carried out in the field as part of the Cellular Test Bed experiments in Newark, N. J. as discussed in Ref. 12. These tests have not only given considerable insight to aid in selection of transmission models and objectives, but also supplied the means by which the design performance could be validated in the field environment.

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