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Experimental Results of 20-Mb/s FSK Digital Transmission on 4-GHz (TD) Radio

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This paper presents the results of tests of 20-Mb/s frequency-shift-keying digital transmission on the 4-GHz TD radio system. On the basis of the test results, the performance of the 20-Mb/s system is projected to be satisfactory to support long-haul digital services. The system employs a 20-Mb/s terminal that multiplexes 12 signals at the first level of digital signal hierarchy (DS-1) (1.5 Mb/s) into a 10-Mbaud, 4-level signal to be transmitted by the Bell System standard 4-GHz (TD) FM microwave radio system. The maximum distance of a digital regeneration span in normal operation is limited by the intermodulation noise to approximately 10 typical hops of TD radio. The 20-Mb/s TD radio system uses the standard frequency-diversity protection switching system, which was designed for analog message service. A fundamental system trade-off is, therefore, the choice of switch threshold: long periods of error-free transmission interrupted by infrequent error bursts due to switch transients versus an occasional low background error rate with less frequent switch transients. We concluded that the protection switch threshold of a 1500-message-circuit channel is suitable for 20-Mb/s TD radio channels.

I. INTRODUCTION

The growth of *Dataphone** Digital Service[1] (DDS)[†] and the needs of new services such as *Picturephone*[‡] Meeting Service[2] (PMS) require a substantial increase in digital long-haul transmission capacity. The existing long-haul digital facilities, mainly Data-Under-Voice[3] (DUV), are near exhaustion in many areas. Furthermore, some existing frequency modulation (FM) radios will be replaced by the single-sideband

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* Service mark of AT&T.

[†] Acronyms and abbreviations are defined in the Glossary at the back of this paper.

[‡] Service mark of AT&T.

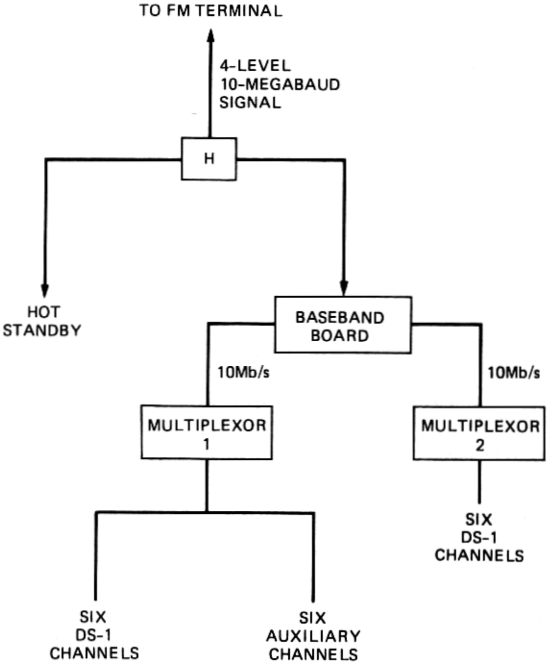

Fig. 1—The 20-Mb/s terminal.

AR-6A[4] radio to increase analog transmission capability. Such replacement reduces the number of DUV channels. New technologies, such as 45-Mb/s transmission on TD radio[5,6] (TD-45A[7,8]) and long-haul digital radio at 4 GHz, will not be available until 1983 and beyond. During the interim, the 20-Mb/s TD system* will be used to provide long-haul digital connectivity.

AT&T Long Lines is deploying an approximately 3000-mile, 20-Mb/s TD network in 1981 and 1982 for DDS application. By the end of 1982, the 20-Mb/s network will have 70 terminals providing 159 digroups. This number of DDS digroups will double the capacity of the 1980 DDS network. The 20-Mb/s terminal has other applications in the Bell System. For example, a portable microwave radio facility can be set up quickly to work with the 20-Mb/s terminals to carry digital services on a temporary basis.

The 20-Mb/s terminal is capable of multiplexing up to 12 asynchronous signals at the first level of digital signal hierarchy (DS-1) into a 9.856-Mbaud, 4-level signal (see Fig. 1). This 4-level signal can be transmitted on the long-haul microwave network using standard FM

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* Using the VIDAR DM-12A 20-Mb/s terminal.

terminals and a dedicated 20-MHz bandwidth radio channel suitable for 1500-message-circuit loading. Recommended maximum digital regeneration span is ten TD radio hops (about 250 miles). The existing 100A[9] or 400A[10] protection switch equipment will protect against propagation fading and radio equipment failures.

Following a summary of the test results in Section 2, the test system configuration and the deployment of test equipment are discussed in Section 3. Section 4 records six tests in the absence of multipath fading, e.g., the jitter performance test, fade margin measurements, and the protection switch compatibility test. Section 5 discusses the performance under the multipath fading condition. The projected performance of the 20-Mb/s TD system for DDS and PMS is discussed in Section 6.

Subsequent to these tests, we found that the preferred power level at the input to the Frequency Modulation Transmitter (FMT) could be reduced by 2 dB, from −14.9 dBm to −16.9 dBm. Combined with the use of a narrower band receiver filter, this power reduction improves the adjacent channel interference and the intermodulation noise performance significantly without degrading the performance of the 20-Mb/s channel. The results presented in this report have been adjusted to reflect the reduced drive level and the tighter receiver filters that are being implemented.

II. SUMMARY

Tests of a 20-Mb/s terminal on a 12-hop, 188-mile TD radio loop were conducted in New Jersey from July to November, 1980. The main results are as follows:

(*i*) It satisfactorily transmitted the digital signal over 12 hops of TD radio without baseband digital regeneration.

(*ii*) The 20-Mb/s terminal showed satisfactory jitter performance.

(*iii*) The system is essentially error-free during normal propagation and operating conditions. System performance as tested in New Jersey is satisfactory for DDS and PMS.

(*iv*) The required cochannel Carrier-to-Interference Ratio (CIR) into a desired 20-Mb/s TD channel is 25 dB at the protection switching point.

(*v*) A switch transient of the 100A frequency-diversity protection switch causes a 6 to 30 millisecond burst of errors. The switch threshold of a 1500-message-circuit channel is suitable for the 20-Mb/s TD channel.

Despite the fact that the protection switch transients will cause transmission errors, the tests confirmed that the use of the 20-Mb/s terminal with the TD radio system can meet long-haul transmission requirements.

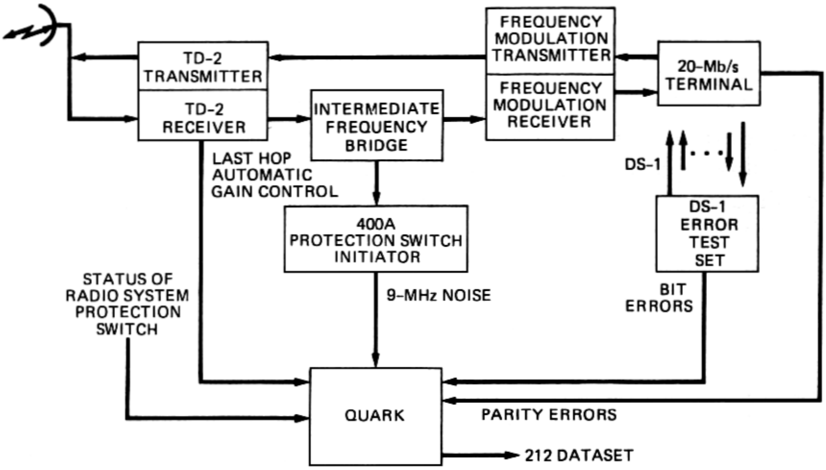

Fig. 2—20-Mb/s TD radio system: test arrangement in Freehold, NJ.

III. TEST DESCRIPTION

The 20-Mb/s TD radio system under test consists of a 20-Mb/s terminal, a 4A FM terminal, a 12-hop loop of TD-2 radio, and a 100A frequency-diversity protection switch (Section 3.1). Two bit-error-rate test sets (Bowmar), an errored-bit accumulator, a 400A protection switch initiator, and a Quantizer, Analyzer, and Record Keeper (QUARK)[11] were used to monitor and to record the performance statistics (Fig. 2).

3.1 System configuration

The 20-Mb/s terminal multiplexes six even-numbered and six odd-numbered DS-1 (1.544 Mb/s) channels into two 10-Mb/s rails and then encodes the two rails into a 4-level, 10-Mbaud baseband signal. The 4-level, 10-Mbaud baseband signal is connected to an FM terminal that provides Frequency Shift Keying (FSK) modulation and demodulation. The FM terminal is then connected to the TD-2 radio via Intermediate Frequency (IF) cables. The baseband power level at the input to the FMT and the output of the Frequency Modulation Receiver (FMR) were −16.9 dBm and −0.9 dBm, respectively.

The test radio route consisted of two 2-way, 4-GHz radio channels connecting Freehold (FH) and Cherryville (CH), NJ, as shown in Fig. 3. All radio units used in the test were TD-2, retrofitted with solid-state microwave generators. The radio channels are suitable for 1500-message-circuit loading.

3.2 Deployment of test equipment

The switch initiator of a frequency-diversity protection system de-

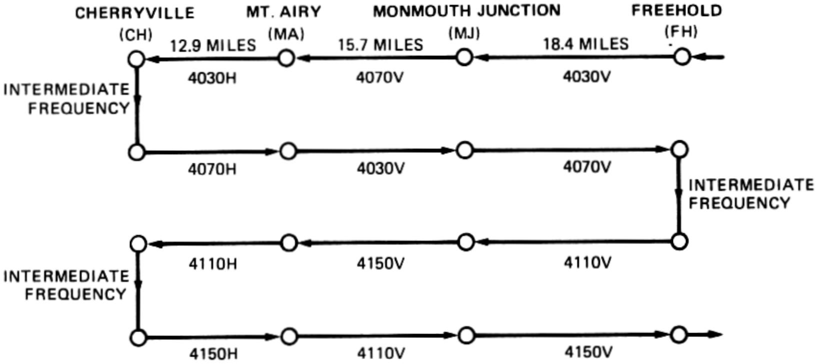

Fig. 3—Frequencies (in megahertz) of TD radio channels for a digital transmission experiment in New Jersey.

tects the noise power in a 1.74-kHz bandwidth centered at 8.9 MHz at the end of a switch section to determine if a working channel needs protection. We therefore installed a 400A protection switch initiator in the receiving IF path to measure the amount of accumulated channel fading over the entire 12-hop route (Fig. 2). For convenience, the power in the 1.74-kHz bandwidth centered at 8.9 MHz will be referred to as the 9-MHz (slot) noise power in the rest of the text.

3.3 Data acquisition system

A QUARK was installed in the Freehold station to record the Automatic Gain Control (AGC) voltage of the last receiving main amplifier and the 9-MHz slot noise of the 12-hop FM radio route, switch activities, errors in two DS-1 channels, and the parity errors in data rail one (9.8 Mb/s, 3672 bits/frame). The statistics of various inputs were accumulated in the QUARK memory. The relationships among DS-1 errors, parity errors, 9-MHz noise, and protection switch activities were studied in terms of statistics of simultaneous events as collected by the QUARK.

IV. TESTS IN THE ABSENCE OF PROPAGATION FADING

Tests were performed to characterize the system performance under normal operating conditions, as well as under controlled stressing conditions. These tests and their results are described in the following sections.

4.1 Baseband spectrum

Figure 4 shows the received baseband spectra of the 20-Mb/s signal measured at FMR-OUT with and without the 12-hop radio loop. The digital spectrum is down about 15 dB at 6 MHz. The 9-MHz noise

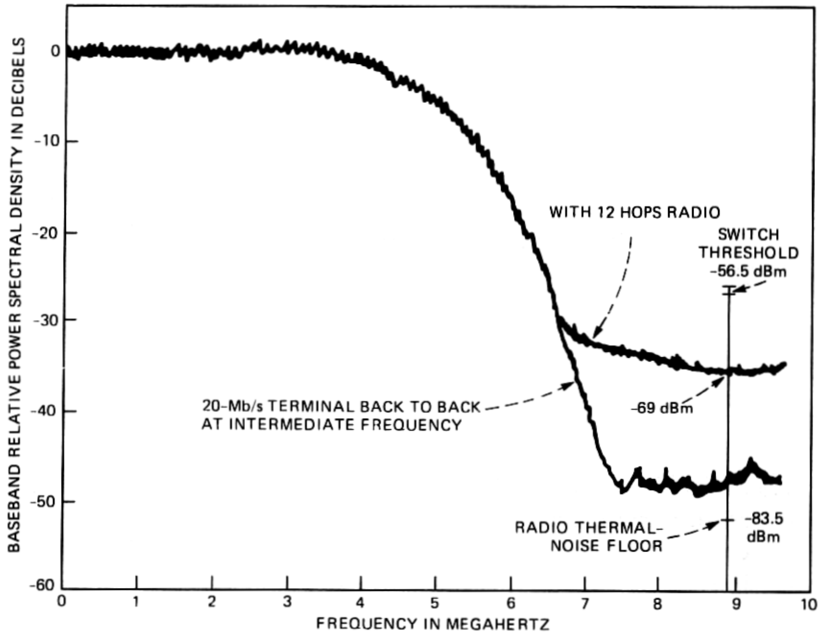

Fig. 4—Baseband spectrum.

power was −69 dBm and −83.5 dBm, with and without the 20-Mb/s modulation, respectively. The 14.5-dB difference represents the 12-hop accumulated intermodulation noise, which dominates the 9-MHz slot noise.

4.2 S/N at baseband versus BER at DS-1 level

Baseband noise was injected before the baseband receiver filter to stress the 20-Mb/s transmission. The main objective was to study the Bit Error Rate (BER) versus baseband signal-to-noise ratio (s/n) relationship.

Figure 5 shows the BER performance of the even- and odd-numbered DS-1 channels of the terminal. The odd-numbered channels perform better than even-numbered channels by 1 dB in s/n for equal BER. This difference is due to the circuit design of the terminal. The 20-Mb/s signal consists of two 10-Mb/s rails. At the terminal receiver, the odd-numbered DS-1 channels are derived from a 10-Mb/s rail, which is decoded from the plus-minus sign decision of the received 10-Mbaud, 4-level signal. The even-numbered DS-1 channels are derived from the other 10-Mb/s rail, which is decoded from the amplitude threshold decision of the received 4-level signal. The plus-minus sign decision is more robust than the amplitude threshold decision by 1 dB

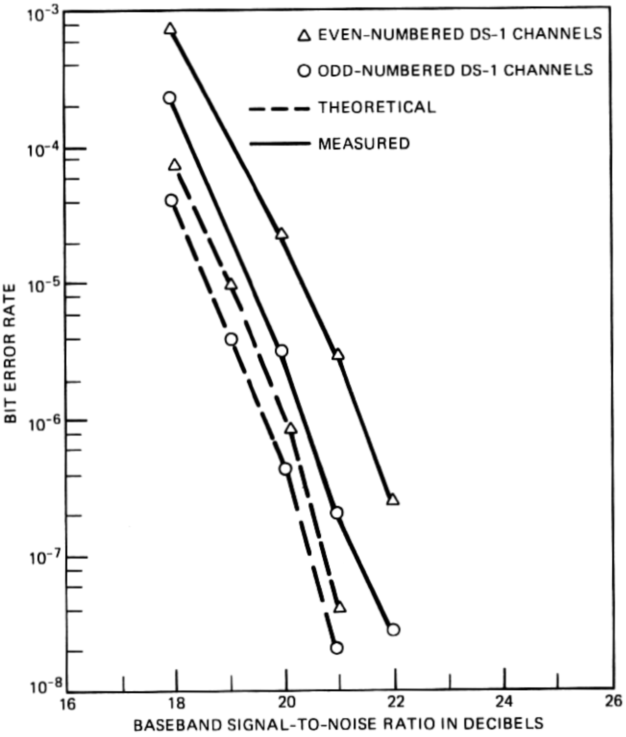

Fig. 5—Bit error rate vs. s/n_{BB} intermediate frequency loopback.

in s/n, as measured, and by 0.5 dB, as theoretically predicted. The theoretical relationship is derived in the appendix. Thus, throughout this study, a discussion of error performance in terms of an even-numbered DS-1 channel implies a conservative (lower) bound on the digital error performance.

Figure 6 shows the measured and calculated BER of the odd-numbered DS-1 channel versus baseband s/n. The 12-hop TD radio degrades the performance of the odd-numbered DS-1 channel by less than 0.5 dB. The effect of 12 hops of TD radio on even-numbered DS-1 channels is practically indiscernible. The maximum regeneration interval (ten TD hops were recommended for the field) is imposed, therefore, by intermodulation noise at the 9-MHz noise slot (Section 4.1), rather than by the digital transmission impairments.

4.3 Jitter performance

Jitter performance of the 20-Mb/s terminal satisfies the requirements of the existing digital network. Under normal operating conditions, the amount of output jitter among DS-1 channels was uniform

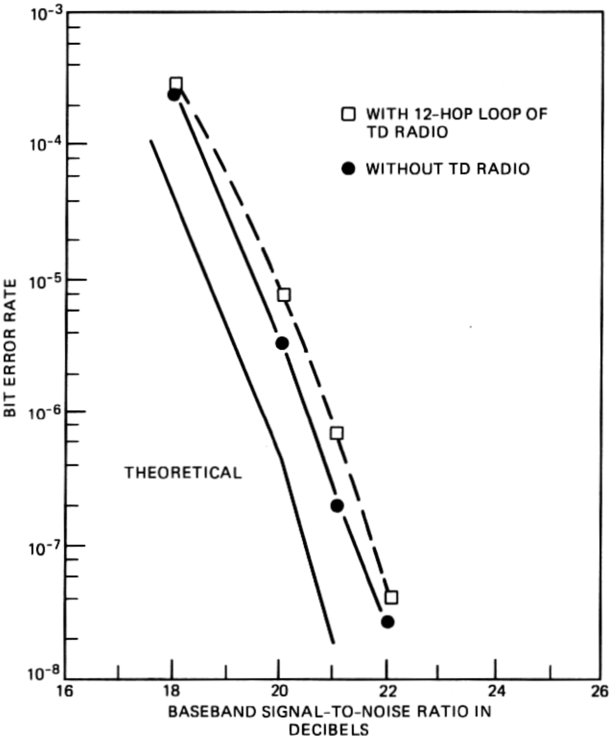

Fig. 6—Bit error rate vs. s/n_{BB} for odd-numbered DS-1 channels.

and comparable to that of the office Quasi-Random-Signal-Source (QRSS), the standard DS-1 signal. In fact, the terminal is effectively a de-jitterizer. The amount of jitter in an output signal was about half that of the input signal, as shown in Table I. Furthermore, digital error performance of two DS-1 channels was compared when the Radio Frequency (RF) signal power was severely attenuated. The channel that took a clean office QRSS as the input consistently made fewer errors than the one that took a jittered source with 11- to 13-percent rms jitter. However, the difference was so small that it was indistinguishable in terms of the fade margin.

4.4 Flat fade margin

The Bell System microwave radio plant was engineered to have adequate flat fade margins to meet the outage objective of allowing less than 0.01-percent outage for all causes over one-way, 4000-mile transmission. The outage of a digital system comprises the time when the one-second-averaged BER exceeds 1×10^{-3}. This objective need

Table I—Jitter performance

	Input to the 20-Mb/s Terminal		Output of the 20-Mb/s Terminal	
	Percent of Jitter (rms)	Percent of Jitter (Peak to Peak)	Percent of Jitter (rms)	Percent of Jitter (Peak to Peak)
1 loop*	13 to 14	60 to 75	5 to 6	25 to 30
2 loops	9 to 11	50 to 65	4 to 5	15 to 25
3 loops	14 to 16	75 to 120	5 to 7	25 to 40
4 loops	15 to 18	90 to 130	7 to 9	35 to 50

* Each loop consists of two complete M13 passes and four hops of digital radio.

Table II—Flat fade margin

Radio Hop	F_s (dB)	F_d (dB)	F_d-F_s
FH-MJ	43.0	43.0	0
MJ-MA	39.3	42.7	3.4
MA-CH	44.0	46.0	2.0
CH-MA	45.0	42.8	−2.2
MA-MJ	41.5	42.5	1.0
MJ-FH	41.5	40.0	−1.5
FH-MJ	39.5	41.5	2.0
MJ-MA	39.5	42.8	3.3
MA-CH	40.5	44.0	3.5
CH-MA	40.0	42.3	2.2
MA-MJ	37.8	39.5	1.7
MJ-FH	38.0	40.0	2.0

F_s = switch point fade margin.
F_d = fade margin to 10^{-6} BER.

not be met on a per-hop basis, because of the existence of severe interference conditions at some junction radio stations, as long as the prorated objective on a per switch section basis was satisfied.

This test measured the required amount of RF attenuation at each radio transmitter to reach the protection switch threshold, which is −56.5 dBm noise power at the 9-MHz slot. This test showed that the fade margin against a BER of 1×10^{-3} always exceeded the switch point fade margin, indicating that the 20-Mb/s TD system can be engineered to meet the facility outage objective. In fact, even the margin against a BER of 1×10^{-6} was generally found greater than the corresponding switch point fade margin. The 10^{-6} margin is of interest because the number of seconds at a BER of 1×10^{-6} at the DS-1 level is an estimate of the number of errored seconds (ES), which is an often referenced service performance parameter.

Table II summarizes the measured switch point fade margins and the 10^{-6} margins of the test system. There were two hops where the BER could exceed 1×10^{-6} before the radio channel would request protection. Since this condition is expected at a few junction stations of the network and we wanted to have a "typical" TD route to conduct this test, no effort was invested to identify the cause and eliminate the situation.

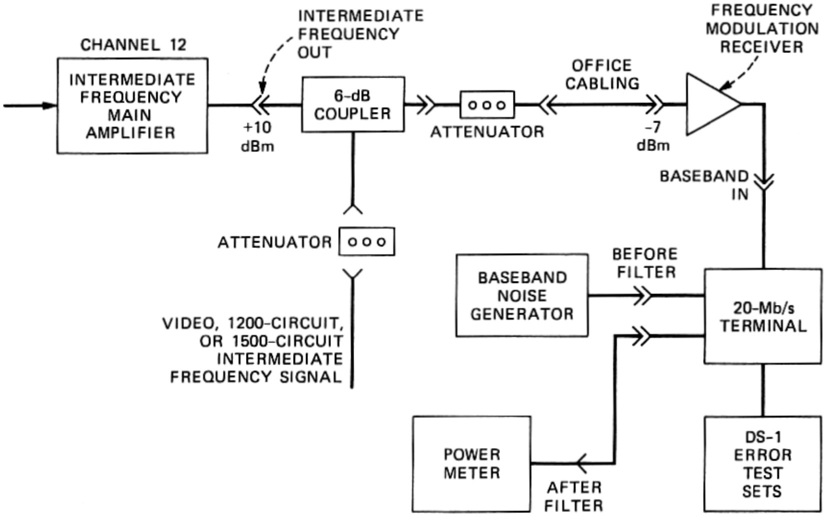

Fig. 7—CIR vs. s/n test setup.

4.5 Effect of cochannel interference

To study the impact of severe cochannel interference on the 20-Mb/s TD channel, an interfering signal was injected at IF. Three kinds of interference signals [i.e., 1200-circuit message, 1500-circuit message, and video (color bar)] were used. The test setup is illustrated in Fig. 7. Figure 8 shows the results for a fixed BER of 1×10^{-6}. The color-bar video signal was observed to be the most interfering; the 1500-circuit message was the least interfering among the three. This is due to the higher concentration of spectral energy near the carrier in certain signals. The baseband filter does not reduce this type of signal appreciably.

At the protection switch initiation point, the s/n versus CIR relationship was also measured, as shown in Fig. 8. In the region where the faded CIR exceeds 25 dB, as the s/n decreases, a protection switch will be initiated before BER degrades to 1×10^{-6}. However, if the faded CIR were less than 25 dB, thermal noise in the radio channel could cause BER to exceed 1×10^{-6} before the switch point. Therefore, severe cochannel interference reduces the effectiveness of the protection switch and degrades the digital error performance.

4.6 Switch system compatibility

For this portion of the test only, a two-way radio channel from Freehold to Cherryville was included in the 100A switching system between these locations. The connection thus had two one-way switch

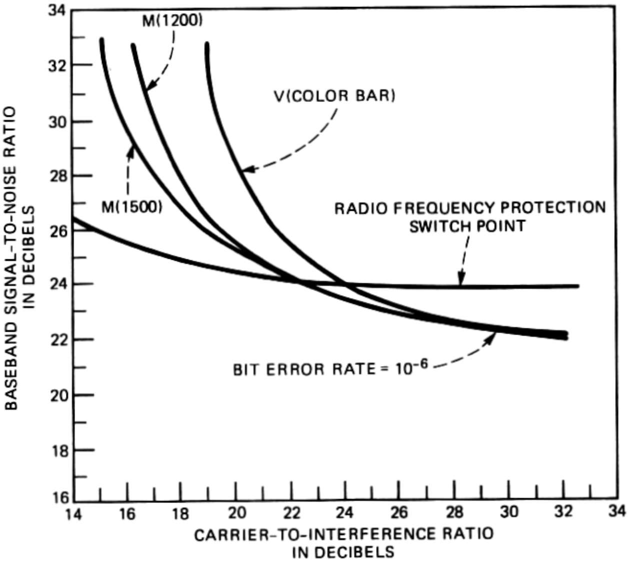

Fig. 8—CIR vs. s/n_{BB} for even-numbered DS-1 channels.

sections, each consisting of three hops of TD radio. Test results include:

(*i*) A switch cycle (to and back from the protection channel) consists of two transients, i.e., two interruptions in data transmission. More than one switch cycle in a second is possible, and the time span from initial loss of signal to the resynchronization of the receiving part of the 20-Mb/s terminal is approximately 30 milliseconds.

(*ii*) No special modification to the 100A switch equipment is necessary. The frequency-diversity protection switch is compatible with the 20-Mb/s TD radio system.

V. PERFORMANCE UNDER MULTIPATH FADING CONDITION

5.1 Amount of multipath fading activity

During the period from July 10, 1980 to August 13, 1980, the impact of multipath fading over the test route was studied. Figure 9 shows the statistics of the 9-MHz slot noise during this period. The measured distribution of 9-MHz noise displayed the inverse slope of 10 dB per decade of probability (the L^2 law[12]). This slope is a well-known characteristic of multipath fading for unprotected radio. The number of events was greater than the number of seconds when the 9-MHz noise exceeded a given abscissa. This observation suggests that multiple switch requests could occur in a second. A switch transient causes errors, and, therefore, frequency-diversity protection is expected to

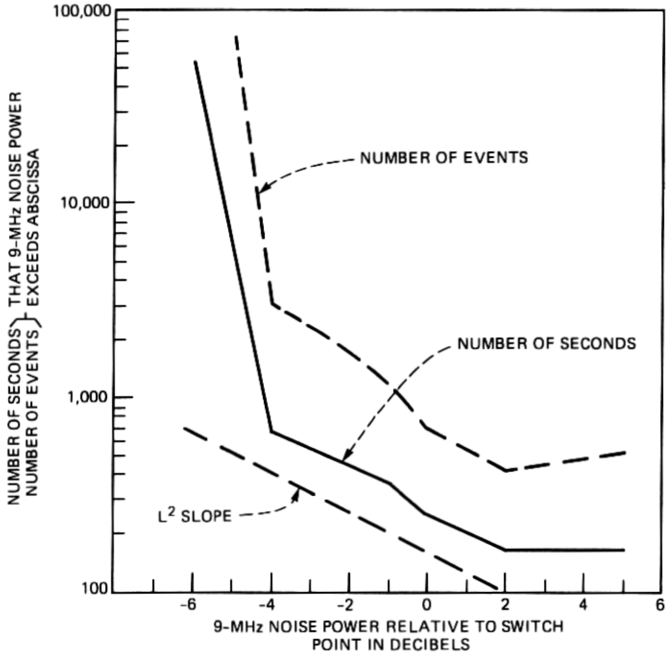

Fig. 9—Distribution of time and events of 9-MHz noise power. The time period monitored was July 10, 1980 through August 13, 1980.

offer limited reduction in the number of errored seconds during multipath fading periods.

The fading statistics of a single hop from Monmouth Junction (MJ) to Freehold are shown in Fig. 10. The solid curve in Fig. 10 also has an inverse slope of 10 dB per decade of probability. The engineering model[12] predicted 166 seconds below 30 dB for this hop during a heavy fading month. We recorded 115 seconds, which is about two thirds of a heavy fading month. Hence, we did experience a fair amount of multipath fading during the test.

5.2 Digital error performance

The measured distribution of BER of an even-numbered DS-1 channel is shown in Fig. 11. There were 432 errored seconds (ES); 263 of them have BER exceeding 10^{-3}. The BER statistics for simultaneous errored seconds of even-numbered and odd-numbered DS-1 channels were also plotted in Fig. 11. They differ in the number of low-BER ES, as expected (see Section 4.2 and the appendix). The number of ES in even-numbered DS-1 channels is approximately 25 percent more than the ES in odd-numbered DS-1 channels.

The data format of the terminal multiplexor contains one parity bit

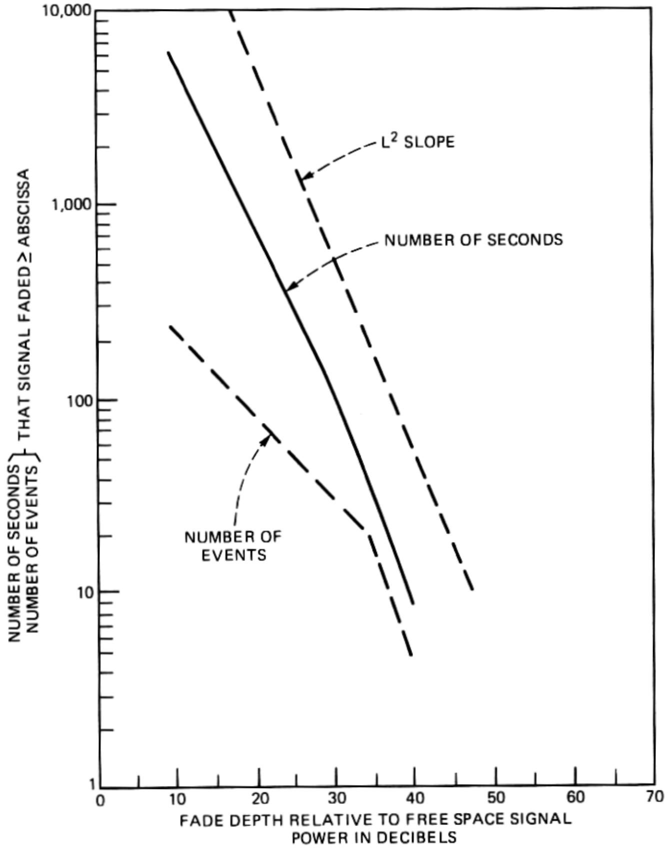

Fig. 10—Distribution of time and events of received signal power. The time period monitored was July 10, 1980 through August 13, 1980.

in a 3672-bit frame. Fault-detection algorithms internal to the terminal and a real-time error-performance monitoring plan to be used by the AT&T Long Lines operations personnel depend on the detection of the parity violations. The distribution of parity violations in a 9.8-Mb/s rail (which feeds six DS-1 channels) can be found in Fig. 12. Those parity violation seconds occurring simultaneously with the ES for the information bits of one even-numbered DS-1 channel are also plotted in Fig. 12. The difference between the two was found to be insignificant. The parity violation seconds offers an effective representation of the real DS-1 ES.

5.3 Relationship between digital errors and 9-MHz noise

Figure 13 shows the distribution of BER of an even-numbered DS-1 channel and the portion of the errored seconds with 9-MHz noise

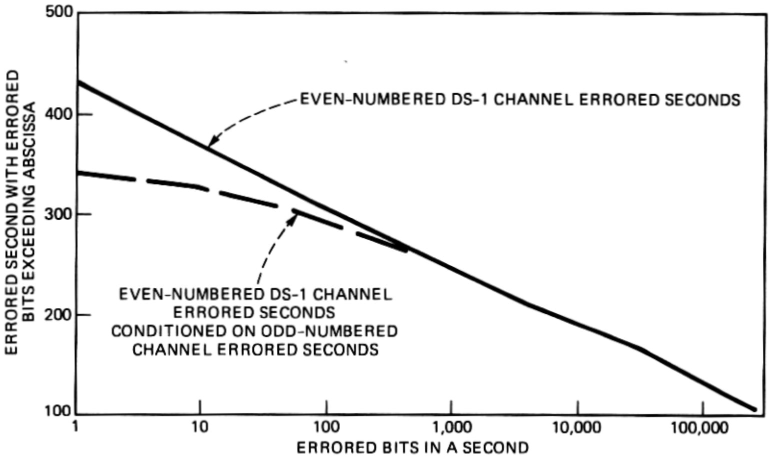

Fig. 11—DS-1 errored-second statistics for the time period July 10, 1980 through August 13, 1980.

exceeding switching point from August 14, 1980 to September 20, 1980. About 10 percent of the errored seconds occurred before the 9-MHz noise reached the switching threshold. All ES with more than 100 errors occurred at the same time the 9-MHz noise exceeded the switch point. Thus, these errored seconds are likely to be accompanied by switch activities in the plant environment.

5.4 Impact of frequency-diversity protection

Based on the assumption that the protection channel is always available for error-free transmission, this section will show that:

(*i*) The switching threshold of a 1500-message-circuit loaded channel is suitable for a 20-Mb/s TD channel, and

(*ii*) During multipath fading periods, the protection switch would have offered little improvement in terms of ES reduction owing to the frequent switching activities.

Under the assumption of perfect frequency-diversity protection, those errored seconds that occurred while the 9-MHz noise exceeded the switching threshold would have been prevented. The exception would be those seconds in which the 9-MHz noise passes through the switching threshold. This is because the actual switch transfer causes an errored second. Based on the observation that a switch cycle could be completed within a second (Sections 4.6 and 5.1), we estimate the number of seconds containing switching activities by the number of seconds in which the maximum value of the measured 9-MHz noise in a second exceeded the switching threshold. Hence, if the test route had been frequency-diversity protected, we would have X ES, where

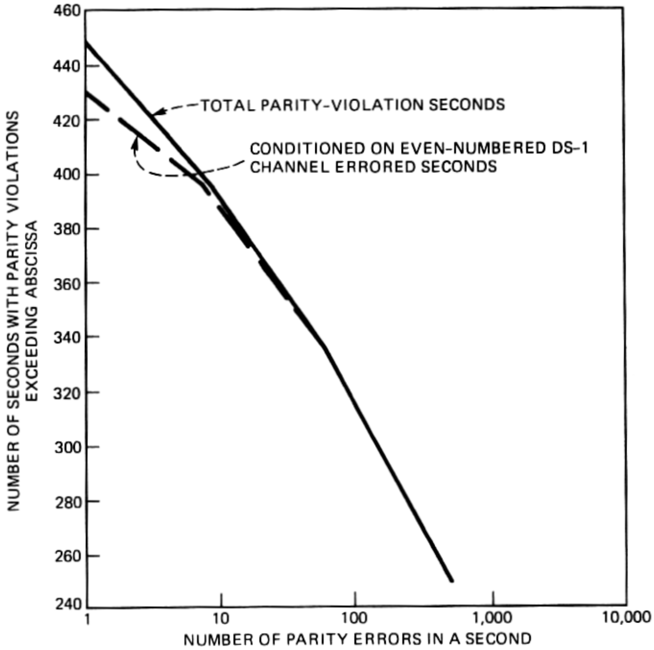

Fig. 12—Parity-violation-second statistics for the time period July 10, 1980 through August 13, 1980.

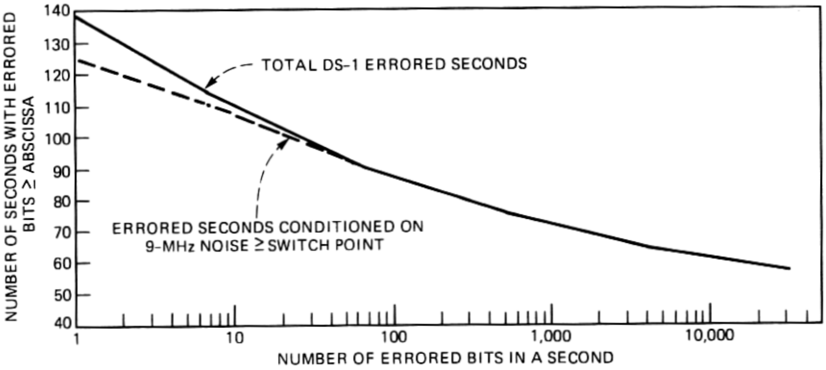

Fig. 13—DS-1 errored-second statistics for the time period August 14, 1980 through September 20, 1980.

X(at a given threshold) =

(Total ES) − (ES conditioned on 9-MHz noise power ⩾ threshold)

\+ (number of seconds with maximum 9-MHz noise power

⩾ threshold).

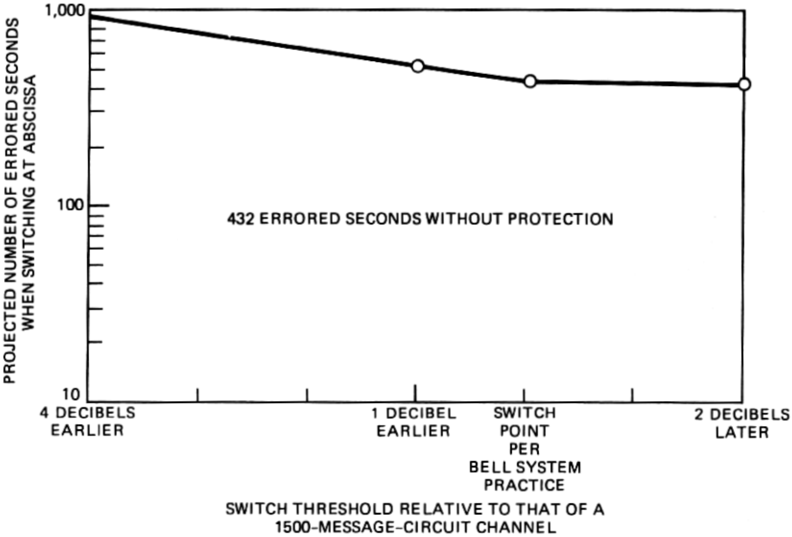

Fig. 14—Sensitivity of switch threshold to errored-second performance projection based on data collected July 10, 1980 through August 13, 1980.

Figure 14 shows the projected number of ES as a function of switching threshold. The projected number of ES decreases as the switch threshold decreases until the switch threshold reaches the level of a 1500-message-circuit loaded channel. Since the 20-Mb/s channel will coexist with 1500-message-circuit loaded channels in the plant, it is desirable from operations and maintenance considerations to use the switch threshold of a 1500-message-circuit loaded channel for a 20-Mb/s TD channel.

VI. PERFORMANCE PROJECTION FOR DDS AND PMS

A properly engineered 20-Mb/s TD system can meet the long-haul outage and quality objectives for DDS and PMS. The long-haul outage objective[13,14] for DDS or PMS is the same as that for Message Telecommunications Service (MTS). Engineering guidelines for TD radio were developed to meet the MTS outage objective and, therefore, those for DDS and PMS as well.

The following demonstrates the ability of the 20-Mb/s TD system to meet the long-haul quality objectives for DDS and PMS.

6.1 Meeting the DDS quality objective

6.1.1 The DDS quality objective

The quality objective of the DDS transmission design requires 99.5-percent error-free-seconds at DS-0 (56-kb/s rate) for 4000-mile, one-way, end-to-end transmission. The test results showed that 90 percent of the errored seconds would be associated with switch transients, which cause errors in all 23 DS-0 channels of a DS-1 signal. We, therefore, assume as a worst case that the DDS quality objective for the 20-Mb/s TD system is the same at DS-0 and DS-1 levels. The objective is thus to have less than 0.5-percent ES for a one-way, 4000-mile transmission.

6.1.2 Generalized performance projection

The majority (ninety percent in this test) of ES of a properly engineered 20-Mb/s TD radio system are expected to be caused by protection switch transients. Therefore, to project the performance of a 20-Mb/s TD system, the statistics of switch activities in a 4000-mile TD route must be considered.

Every switch system (e.g., 100A, 400A) has a switch register that counts the number of automatic switch completions. Any manually forced protection switches for routine maintenance are not included in these counts. AT&T Long Lines records the number of switches on a weekly basis. These records of switch completions from June 16, 1979 through June 7, 1980 on five TD routes (New York City to Boston, New York City to Philadelphia, Philadelphia to Silver Spring, Pittsburg to Silver Spring, and Chicago to Kalamazoo) suggest that there are 13,500 switch completions per year for an average one-way radio channel for multipath fading protection in a 4000-mile TD radio system. There could be two errored seconds associated with a switch cycle; therefore, 27,000 ES due to multipath fading are expected annually.

The one-year switch register data also revealed that, in addition to the switchings due to multipath fading, there were protection switches, called the background switch activities, which were attributed to craft activities, hardware problems, and other causes. These background switches are of a transient nature. A switch cycle lasts much less than a second. According to the same database, this type of switch amounted to 0.03 switch completion per mile per week per channel on average. Thus, we project 6240 ES due to background switches.

Table III summarizes the projected number of ES in a year due to all causes. The total number of ES is 34,078 which is 0.11 percent of a year. This projection compares favorably with the objective of 0.5 percent and shows that the 20-Mb/s TD system performance is satisfactory for DDS.

6.2 Meeting the PMS quality objective

We have observed essentially error-free performance without fading. Multipath fading seldom occurs during an 8 am to 9 pm business day,[12]

Table III—Projection of errored seconds caused by switching in a one-way, 4000-mile TD route in a year

Cause	Errored seconds
FMT or 20-Mb/s terminal failure	18
Routine maintenance	720
Radio failure	100
Background switch activity	6240
Multipath fading	27,000
Total	34,078
	=0.11 percent/year

when most PMS calls will take place. Therefore, based on the rate of background switches, as discussed in the previous section, we project that the 20-Mb/s system performance is satisfactory for PMS.

VII. ACKNOWLEDGMENT

Many colleagues at Bell Laboratories and AT&T Long Lines offered their prompt assistance at every stage of this project. I am particularly grateful to L. A. Dietrich and S. H. Lin for their participation and technical guidance throughout the project. The QUARK was designed by T. G. Szekeres and G. A. Zimmerman.

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APPENDIX

Predicted Error Performance With Ideal Channel Plus Gaussian Noise

This appendix approximates a set of relationships between a 1-second bit error rate at DS-1 level and the baseband signal-to-noise ratio based on our understanding of the 20-Mb/s terminal and an idealized FM channel with Gaussian noise.

There are two multiplexor units in the main/working portion of a terminal. The number 1 multiplexor unit accepts data from the six odd-numbered DS-1 channels plus the six auxiliary (AUX) channels. The number 2 multiplexor unit accepts data from six even-numbered DS-1 channels. Each multiplexor combines its inputs into a single data-bit stream of 9.856 MHz. These two bit streams form binary groups: the first digit in the binary group is taken from the number 1 multiplexor, the second from the number 2 multiplexor. These binary groups are Gray coded and are then converted into a single 4-level signal. It has been verified in the laboratory that the four levels at the transmitter output are indeed equally spaced.

The decoder at the terminal receiver performs the inverse operation. The probabilities of error for even- and odd-numbered DS-1 channels separately can be derived in a manner similar to the analysis of Lucky[15] and others under the following assumptions:

1. The amplitudes of the four symbols are equally likely to assume any of the four equally spaced values $\pm d$ and $\pm 3d$. Symbols occurring at different times are independent.

2. The bit error performance of the terminal depends on s/n but is insensitive to the spectral shape of noise. (This has been verified in the laboratory.) We assume that the additive noise is Gaussian.

3. The pulse shaping $X(w)$ is raised cosine with 50 percent roll-off:

$$X(w) = \begin{cases} T & 0 \leqslant w \leqslant \dfrac{\pi}{2T} \\ \dfrac{T}{2}(1 + \sin wT) & \dfrac{\pi}{2T} \leqslant w \leqslant \dfrac{3\pi}{2T}, \end{cases}$$

where T is the baud interval.

The terminal puts all pulse shaping at the transmitter. Therefore, the signal power input to the FM channel is:

$$p_s = \frac{\overline{a^2}}{2\pi T} \int_{-\infty}^{\infty} |X(w)|^2 dw$$

$$= \frac{35}{8} d^2,$$

where $\overline{a^2}$ is the average symbol power, $\overline{a^2} = 5d^2$.

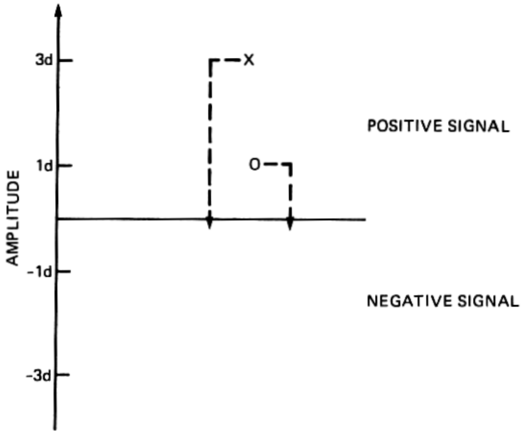

Fig. 15—Error occurrence in an odd-numbered DS-1 channel.

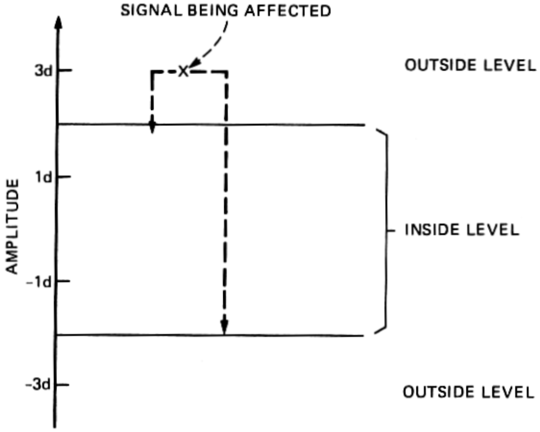

Fig. 16—Error occurrence of an outside-level signal in an even-numbered DS-1 channel.

The receiver detects the signal levels and places slicing levels at 0 and $\pm 2d$. An error occurs when the noise at a sampling time pushes the received signal amplitude (voltage) across the slicing levels. The slicing level drift due to noise is assumed insignificant. The probability of a signal being at one of the outside two levels equals that of being at one of the inside two levels. A signal at the outside level, or inside level, can only cross the zero level in one direction when the noise voltage $|y|$ exceeds $3d$ or d, respectively, as illustrated in Fig. 15. Therefore, the probability of error for an odd-numbered channel is:

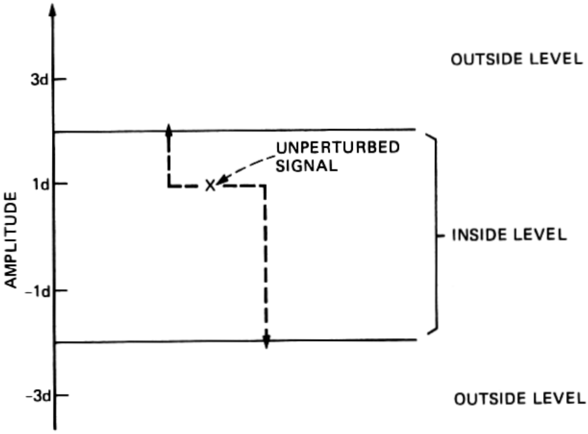

Fig. 17—Error occurrence of an inside-level signal in an even-numbered DS-1 channel.

$$\begin{aligned} p^{\text{odd}} &= \tfrac{1}{2} \cdot \tfrac{1}{2} p(|y| > 3d) \\ &\quad + \tfrac{1}{2} \cdot \tfrac{1}{2} p(|y| > d), \end{aligned} \tag{1}$$

where $p(|y| > d)$ represents the probability of noise voltage exceeding d.

The probability of error for an even-numbered channel, p^{even}, can be derived similarly. The probability of a signal in the outside state is ½. For that signal to be in error, the noise in one direction only with a magnitude $|y|$,

$$5d > |y| > d$$

is required, as illustrated in Fig. 16. The probability of a signal in an inside level crossing a $\pm 2d$ slicing level is $p(|y| > d) - \tfrac{1}{2} p(3d > |y| > d)$, as shown in Fig. 17. Therefore,

$$\begin{aligned} p^{\text{even}} &= \tfrac{1}{4} p(5d > |y| > d) \\ &\quad + \tfrac{1}{2} p(|y| > d) - \tfrac{1}{4} p(3d > |y| > d) \\ &= \tfrac{1}{4} p(|y| > d) - \tfrac{1}{4} p(|y| > 5d) \\ &\quad + \tfrac{1}{2} p(|y| > d) \\ &\quad - \tfrac{1}{4} p(|y| > d) + \tfrac{1}{4} p(|y| > 3d) \\ &= \tfrac{1}{2} p(|y| > d) + \tfrac{1}{4} p(|y| > 3d) \\ &\quad - \tfrac{1}{4} p(|y| > 5d). \end{aligned} \tag{2}$$

This probability is easily computed since the noise at the receiver input is assumed Gaussian. The probability of noise voltage exceeding

d is conveniently expressed in terms of the normal probability integral, $p(|y| > d) = 2Q\left(\frac{d}{\sigma}\right)$, where

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-t^2/2}\, dt$$

and σ is the root-mean-square (rms) noise voltage.

The signal to noise power ratio, p_s/p_N, can be expressed as

$$\frac{p_s}{p_N} = \frac{35d^2}{8\sigma^2}.$$

Hence, eqs. (1) and (2) become

$$\begin{aligned} p^{\text{odd}} &= \frac{1}{2}\left\{Q\left[3\left(\frac{8X}{35}\right)^{1/2}\right] + Q\left[\left(\frac{8X}{35}\right)^{1/2}\right]\right\} \\ p^{\text{even}} &= \frac{1}{2}\, Q\left[\left(\frac{8X}{35}\right)^{1/2}\right]\left\{1 - 2Q\left[5\left(\frac{8X}{35}\right)^{1/2}\right]\right\} \\ &\quad + Q\left[\left(\frac{8X}{35}\right)^{1/2}\right] \\ &\quad - \frac{1}{2}\, Q\left[\left(\frac{8X}{35}\right)^{1/2}\right]\left\{1 - 2Q\left[3\left(\frac{8X}{35}\right)^{1/2}\right]\right\}, \end{aligned}$$

where $X = \frac{p_s}{p_N}$.

A digital computer was used to compute the probabilities of error as a function of the baseband signal-to-noise ratio. Results are discussed in Section 4.2.

GLOSSARY

AGC	Automatic gain control circuitry
AM	Amplitude modulation
AR-6A	A Western Electric 6-GHz single-sideband AM microwave radio system
BER	Bit error rate
CIR	Carrier-to-interference power ratio, expressed in dB
DDS	*Dataphone*® Digital Service, a synchronous full-duplex digital service at 2.4-, 4.8-, 9.6-, and 56-kb/s rates on point-to-point and multipoint bases
DS-0	Digital signal at the 0th level of the TDM hierarchy, the DS-0 level; a signal at the 64-kb/s rate, the DS-0 rate

DS-1	Digital signal at the 1st level of the TDM hierarchy, the DS-1 level; a signal at the 1.544-Mb/s rate, the DS-1 rate
DUV	Data under voice, a system that provides for the transmission of one DS-1 signal over an FM microwave radio link. (This system is also known as 1A radio digital system.)
ES	Errored second; a second that contains at least one errored bit
EFS	Error free second
FM	Frequency modulation
FMT/FMR	Frequency modulation terminal transmitter/receiver
FSK	Frequency shift keying
IF	Intermediate frequency (70-MHz ± 10-MHz for TD radio)
MTS	Message Telecommunications Service
PMS	*Picturephone*® Meeting Service, a switched, common-user, interactive visual and audio teleconferencing service offered between two remote conference room locations
s/n	Signal-to-noise ratio in dB
TD-45A	A system for 45-Mb/s digital transmission over the TD radio network
TDM	Time division multiplexing, the process of combining a number of digital signals into a single digital stream by an orderly assignment of time slots
TD-2	A Western Electric point-to-point 4-GHz microwave radio transmission system