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1969-70 Connection Survey:

High-Speed Voiceband Data Transmission Performance on the Switched Telecommunications Network

By M. D. BALKOVIC, H. W. KLANCER, S. W. KLARE, and W. G. McGRUTHER

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In this article we present estimates of data transmission error performance at data rates of 1200, 2000, 3600 and 4800 b/s on the Bell System Switched Telecommunications Network. The source data was collected as part of the 1969–70 Connection Survey conducted by Bell Laboratories. Results are based on measurements made on approximately 600 toll connections, dialed from 12 receiving to 92 transmitting sites in the United States and Canada. Standard Bell System Data-Phone® *data sets were used to transmit and receive the digital signals.*

Distributions of errors per call are given on a bit, burst and block basis. Information is also presented on the distribution of intervals between errors, the structure of error bursts, and the number of errors in blocks of various sizes. Some discussion is given on error causes observed for operation at 2000 b/s.

Results of error rate measurements indicate that for operation at 1200 and 2000 b/s approximately 82 percent of the calls have error rates of 1 error in 10^5 bits or better, assuming an equal number of short-, medium-, and long-haul calls. This represents a substantial improvement of performance in comparison with results of previous surveys. For each of the four data rates tested, 1000-bit block error rates of less than one block error for every 10^2 data blocks transmitted are achieved on 80 percent of the calls. For operation at 2000 b/s, a major cause of errors is shown to be impulse noise.

I. INTRODUCTION

Data-Phone service was introduced on the switched network in 1959. Since that time, the number of data sets in service has grown by approximately 50 percent per year, resulting in the connection of over 100,000 data terminals by 1970. A wide variety of data system applications has evolved with the trend being toward higher speeds, automatic operation, improved performance, and lower costs.

Since 1959 the overall switched telecommunications network has also experienced substantial growth and change. During this period the annual growth rate of the number of miles of voiceband channels in the network has been approximately 19 percent. More than half of the facilities in service today have been placed in service since 1959. Accompanying this growth has been the introduction of newly designed transmission and switching equipment. In addition, the growth of data services has resulted in data transmission considerations being reflected to a greater extent in the overall design, operation, and maintenance of the switched network.

Since the network has undergone considerable change there is a need for current information on performance. Such information is of value in the design of data systems including the design of modems and error control procedures. It is also of use in establishing performance objectives and in identifying areas where service improvements may be realized.

A number of surveys conducted in the past by BTL have provided information on the data transmission characteristics of the switched network. The most widely known is the report by A. A. Alexander, R. M. Gryb, and D. W. Nast[1] which together with followup reports by E. O. Elliott[2] and R. Morris[3] discusses error performance at 600 and 1200 b/s. Results of other tests conducted at 2000 and 3600 b/s on the switched network also have been reported.[4,5] This report is intended to supplement and update that information.

The results presented in this paper report on data transmission error performance for operation at 1200, 2000, 3600, and 4800 b/s. The source data was collected as part of a large scale field measurement program conducted by Bell Laboratories on the Bell System Switched Telecommunications Network. The purpose of the survey was to obtain current information on the transmission characteristics of dialed toll connections. Emphasis was placed on a detailed characterization of each test call. In addition to high-speed data transmission measurements reported herein, measurements of analog channel parameters such as loss, frequency response, envelope delay, P/AR (peak to average ratio), impulse and message circuit (background) noise, nonlinear distortion, and phase jitter were included in the survey. Results of these measurements are presented in a companion paper by F. P. Duffy and T. W.

Thatcher, Jr.[6] Also included were error performance measurements of operation at 150 b/s. Results of these tests are presented by H. C. Fleming and R. M. Hutchinson.[7]

The next two sections of this paper discuss the sampling plan by which a set of connections was chosen, and the equipment implementation used to carry out the testing of those connections. This is followed by a discussion of the results which is divided into three major sections: per call statistics, fine grain statistics, and causes of errors. Per call statistics are presented in terms of cumulative distribution functions and allow a determination of the percentage of calls exceeding a particular performance level. Bit error rate, burst rate and block error rate information is presented in this manner. Fine grain statistics give information on how errors occur within a call. Examples are burst length, error free gap length, and the probability of a specific number of errors in a block of data. These statistics are generally combined over the set of test calls and are presented as cumulative distributions of the probability of an occurrence.

II. SAMPLING PLAN FOR HIGH-SPEED DATA MEASUREMENTS

A major objective of the 1969–70 Connection Survey was to obtain estimates of data transmission performance achieved by *Data-Phone* service. A straightforward implementation to meet this objective implies sampling data traffic and testing connections between customer locations. Because detailed *Data-Phone* traffic records are not maintained, geographical dispersion was instead achieved by a sampling procedure based on overall toll traffic. This results in an additional complication since some local switching equipment is not suitable for high-speed data service. This equipment was not used, consistent with the present practice of providing high-speed *Data-Phone* service. A further consideration involves the fact that customer dialed connections have three basic parts: the loop between the station and the local switching office, the connection between switching offices, and the far-end loop. Performance is determined by the overall end-to-end characteristics. This implies the necessity of sampling loops as well as the connections between offices. Loops were not included in the basic test connection for several reasons. A loop is dedicated to a particular station, therefore the variability observed between repeated calls dialed from one particular location to another is primarily due to the different connections obtained between the switching offices. Furthermore, loops used for high-speed data transmission are subject to specific transmission requirements[8] which minimize their effect on error performance. Thus, results presented in this paper include only the toll connection between local switching offices. Some discussion is given on results of tests conducted using simulated loops.

The basic elements on which measurements were made were dialed toll connections between Bell System local switching offices. All tests were made during the normal business day; no tests were made at night or on weekends. Connection to the office was at the same point that a customer loop would terminate.

A three-stage sampling plan, stratified into three mileage bands, was used to select the test connections. The basic sampling plan has been described by Duffy and Thatcher[6]; the procedures used are outlined below, with emphasis on the selection of sites for high-speed data transmission tests.

The first stage of sampling resulted in the selection of 12 local switching offices (primary sites). This was done by subdividing the United States and Canada into 12 areas of approximately equal total originating toll traffic. Primary site selection within each subdivision was random with probability of selecting an office proportional to its annual originating toll traffic. Associated with each primary office, far-end local offices (secondary sites) were selected at random based on a record of specific toll traffic originating from the primary site. Secondary sites were stratified into three mileage bands: 0–180, 180–725, and 725–2900 miles distant from the primary. Stratification took place before secondary selection to obtain approximately the same number of test calls in each mileage band. A total of 32 secondary sites was selected in the short mileage band and 33 sites were selected in both the medium and long mileage bands.

Consistent with the sampling plan, all test calls were dialed from the primary site to the secondary site. The test plan called for the characterization of six test calls between each primary-secondary pair.

As discussed earlier, a sample obtained as described above could contain local switching equipment that is not suitable for high-speed data transmission. For example, offices with panel equipment and certain equipment associated with step-by-step (SXS) offices can cause high levels of impulse noise. In providing *Data-Phone* service on the switched network, it is necessary at times to bypass such equipment. Thus, the following procedures were used to modify the sample.

When a primary office containing panel equipment was selected, the measurements were made from an alternate, remote exchange office. The office used was that from which a high-speed data customer would be served if the panel office in fact caused unsatisfactory data transmission performance. One primary office with panel equipment was selected but it also contained crossbar equipment. Thus high-speed measurements were made on the crossbar machine. In the case of panel secondaries, rather than testing at an alternate office, the results were omitted. This was done because the small amount of additional precision which would have been obtained by testing an alternate did not warrant the effort required. Six secondary sites were so affected.

When a primary office containing SXS equipment was encountered, inclusion in the sample was based on satisfactorily meeting the following impulse noise pretest. The number of impulse noise counts in 15-minute periods was measured at a threshold of 69 dBrnC (1 dB below the average received data signal level for a long-haul call[6]). This was done for several test lines from the office throughout the business day. If over 50 percent of the tests exhibited more than 15 noise counts due to office equipment, the survey measurements were made from the remote exchange office. Two such offices were encountered and the alternate offices were used as test sites. It was determined that the impulse noise in the excluded offices was largely caused by switches used to select outgoing trunks. Because all survey test calls were dialed from primary site to secondary site, this source of noise was not a problem at the secondary sites. No secondary offices with SXS equipment were excluded.

The resulting sample used to describe high-speed data performance contained 12 primary offices: seven had crossbar equipment, three had SXS equipment, and two had both crossbar and SXS. There were 92 secondary offices in the sample: 56 had crossbar equipment, 35 had SXS equipment, and one was an ESS office.

III. TEST PROCEDURE AND DATA COLLECTION EQUIPMENT

The general test arrangement is shown in Fig. 1 with emphasis on the data transmission tests. As shown in the figure, test word generators and data set transmitters were located at the secondary site. The data signals were transmitted to the primary site where the data set receivers and associated test equipment were located. Some of the data sets were connected through simulated subscriber loops. Also, an analog-to-digital converter was used to sample the received line signal of one modem.

A digital computer at the primary site monitored the errors and carrier detector activity of the data sets on a bit-by-bit basis. This information was compacted by the computer and transmitted over a 2000 b/s data link to Bell Laboratories at Holmdel, New Jersey, where it was stored on magnetic tape for later analysis. To protect the integrity of the test results, the data link employed error detection with block retransmission for error correction.

To provide a cross reference with the data stored on the tapes and to provide protection against breakdowns of the main data collection system, a backup system was used to collect error rate information. During periods when the main data collection system was inoperative, no bit-by-bit information was collected. However, the backup system continued to collect bit error rate information.

Table I lists the data sets and bit rates that will be discussed in this paper. Included in the table is information on the length of test calls, length of the test words used, and the number of test calls made at each speed. In the implementation of the survey, the Data Set 203 was tested at 3600 b/s at all primary sites with approximately half

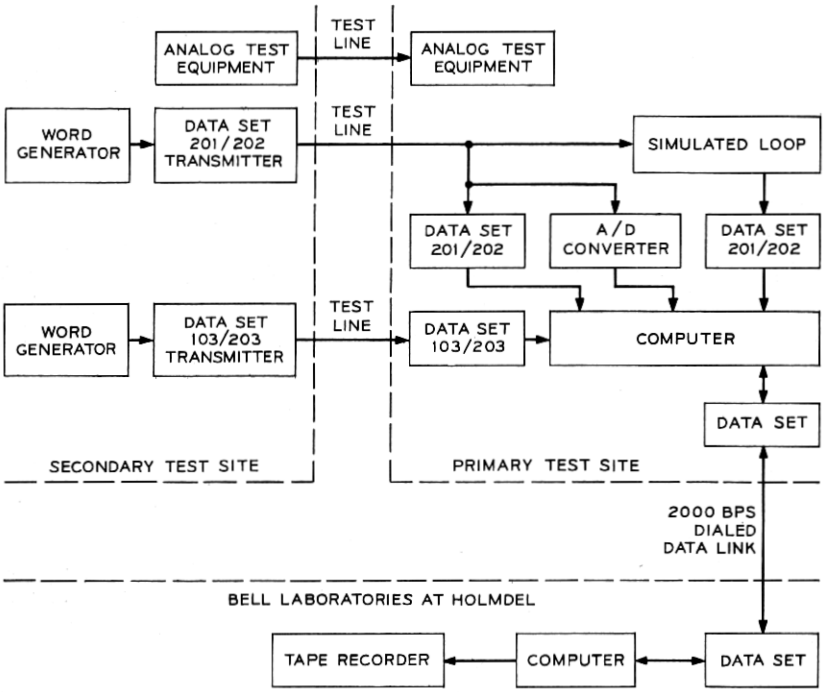

Fig. 1—General equipment arrangement for data set tests.

Table I—Data Set Test Information

Speed (b/s)	Data Set Code	Number of Test Calls	Number of Calls With Bit-by-Bit Data	Length of Data Run (min.)	Test Word (Bits)
1200	202	568	528	30	511
2000	201	567	544	30	511
3600	203	277	270	20	$2^{23} - 1$
4800	203	130	129	20	$2^{23} - 1$

of the secondary sites. It was tested at 4800 b/s from the other half of the secondary sites after the 4800 b/s option became available, approximately half way through the survey. Since this represents approximately 25 percent of the test calls, no information is given by mileage band or on fine grain statistics for operation at 4800 b/s.

3.1 *Test Procedure*

At the beginning of a test day, three test calls were dialed from the primary site to the secondary site. While analog transmission measurements were being made on one connection, voiceband data was transmitted on the other two. Data transmission on one connection was at 1200 and 2000 b/s, each for 30 minutes. On the other connection, tests were made at 150 b/s for 40 minutes and either 3600 or 4800 b/s for 20 minutes. After the completion of these tests, the roles of the test connections were exchanged and the procedure repeated until all tests had been made on all three connections. Upon completion of this sequence, all lines were disconnected and three new calls were dialed. Thus, on an average day, six connections were completely tested. There were occasions when some of the lines were disconnected prematurely; these disconnects were usually attributable to testing errors. Whenever possible, another call was dialed and as many tests as possible were made on the replacement.

As discussed earlier, measurements were made between local switching offices and did not include subscriber loops. To determine the effects on data set performance of the distortion introduced by the amplitude and phase characteristics of loops, the 1200 and 2000 b/s data sets were tested in two configurations. Two data set receivers of the same type were used concurrently; one was connected directly to the incoming line signal and the other was connected through an artificial cable section representing a pair of subscriber loops. Both receivers were simultaneously monitored by the data collection equipment. Artificial cable sections representing various combinations of average and worst-case envelope delay and loss slope for pairs of subscriber loops[8,9] were interchanged from one test to the next. The 3600 and 4800 b/s modems were not tested in this configuration, since they contain adaptive equalizers which compensate for the effect of amplitude and phase distortion.

3.2 *Data Set Tests*

The data sets were operated according to standard Bell System practices. The transmitted line signal was −12 dBm at the serving central office. The 1200 and 2000 b/s receivers were operated using compromise equalizers; the 3600 and 4800 b/s modem used adaptive equalizers. The carrier detectors in all data sets caused the received data to be clamped to steady marking in the event of a carrier off indication. For the data sets with a reverse channel capability, the Data Sets 202 and 203, echo suppressors were disabled prior to data transmission.

A pseudorandom test word was used on the digital channel. After the modems were synchronized, the test word generators were synchronized and the data recording equipment was enabled. For all data sets, the data collection equipment recorded the bit error pattern and carrier fail indication on a bit-by-bit basis.

3.3 *1200 b/s (Data Set 202)*

The Data Set 202 employs frequency shift keying to transmit a signal on the telephone line. For the survey, a 511-bit pseudorandom word (CCITT Standard) was used as the data source at the secondary site. At the primary site, a locally generated version of the test word was compared with the received data signal, and the resulting error signal recorded.

This modem does not provide receiver timing. The timing signal used to operate the data collection equipment was recovered from the zero crossings of the received data bit stream. A stable clock recovery system was used to minimize the occurrences of synchronization loss between the received test word and its locally generated version. The clock used proved sufficiently stable to maintain synchronism during signal interruptions of up to ten seconds.

The Data Set 202 provides a low-speed reverse channel which was enabled during about half of the data runs. At the beginning of each 202 test, a tone was transmitted from receive site to transmit site to disable echo suppressors in the connection and therefore allow simultaneous two-way transmission. On each call it was ascertained whether the reverse channel was operating properly. Failure to receive reverse channel energy was noted on only one test call.

3.4 *2000 b/s (Data Set 201)*

The Data Set 201 employs differentially encoded four-phase modulation. This modem was also tested with a 511-bit pseudorandom word as the data source.

The Data Set 201 provides recovered clock which was used to interpret the received data. Thus, all decisions on errors in the received data were based on this clock signal. However, a stable clock regenerator was used with the data collection equipment. This clock was capable of maintaining synchronism of the local word during clock interruptions of up to ten seconds.

To obtain information on the type of transients affecting the performance of the 2000 b/s modem, an analog to digital converter was used to sample the line signal entering the receiver. When bit errors occurred in the received data stream, the digital computer recorded the corresponding segment of the line signal. In this way, a record of error causing events was maintained. This analog to digital sampling technique was used at six of the 12 primary sites.

3.5 *3600 and 4800 b/s (Data Set 203)*

The Data Set 203 is a multilevel vestigial sideband AM data set which employs automatic adaptive equalization and coherent detection. For this modem, a specific startup procedure is necessary to achieve synchronization. This routine was performed at the beginning of each Data Set 203 test, and there were no test calls on which the modem would not achieve synchronism.

The received timing signal provided by the data set was used to interpret the received data. It can maintain synchronism for at least one second in the absence of line signal.

The Data Set 203 contains a scrambler to maintain the settings of the adaptive equalizer, to provide timing recovery information, and to keep the signal energy on the telephone line constant. This scrambler was used to produce the transmitted bit pattern. It consists of a 23-stage shift register which produces a pseudorandom word when the data input is steady spacing. At the receive end, a descrambler reverses the process. Because of the structure of the scrambler-descrambler, an event on the telephone line which causes a single bit error in the scrambled data results in the recording of three bit errors. The error pattern produced is

1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 1

(the ones represent errors, the zeroes represent error-free bits and the left-most bit is the first bit delivered). This same error pattern is experienced in customer data during error occurrences. The effect of the scrambler will be noted several times in later sections of this paper.

The reverse channel of the Data Set 203 was used on all test calls to send a 511 bit pseudorandom word at 150 b/s concurrent with high-speed data transmission. No measure was made of reverse channel error performance. However, presence or absence of the reverse channel signal was noted. Improper operation occurred in two instances.

IV. BIT ERROR RATE RESULTS

Average bit error rate is the parameter most often used to describe the performance of a digital channel because it is easy to measure and is independent of any particular data system parameters, such as block size. Average bit error rate was determined for each call and is presented in Figs. 2, 3, and 4. These figures show cumulative distribution functions (CDFs) of the bit error rate per call for operation at 1200, 2000, and 3600 b/s in the short, medium, and long mileage strata. The CDFs include errors incurred during carrier off indications. As discussed earlier, the outputs of the data sets are clamped during carrier off indications; because of the randomness of the test words used, a 50 percent error condition is encountered.

In order to relate the sample obtained to the base population, the contribution of each test call to these CDFs is weighted by its probability of inclusion in the sample.[6] Figures 2, 3 and 4 therefore represent estimates of performance for the *Data-Phone* population. They differ only slightly from the sample distributions where each test call contributes equally. Table II presents estimates of the percent of error free calls at the three speeds for the three mileage bands. From Figs. 2, 3 and 4 and Table II, a trend toward poorer performance with increasing distance is evident. However, since for each data set the extremes of the bit error rate distributions in the three mileage categories overlap, the variation within a mileage category is considerably greater than the difference between the categories. The results also show that error rate performance at 1200 and 2000 b/s are comparable while error rates at 3600 b/s are somewhat larger.

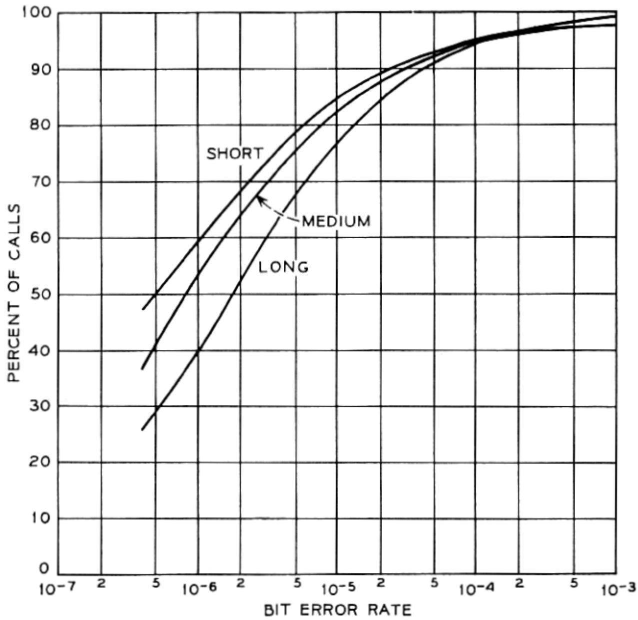

Fig. 2—Bit error rate distributions by mileage strata at 1200 b/s.

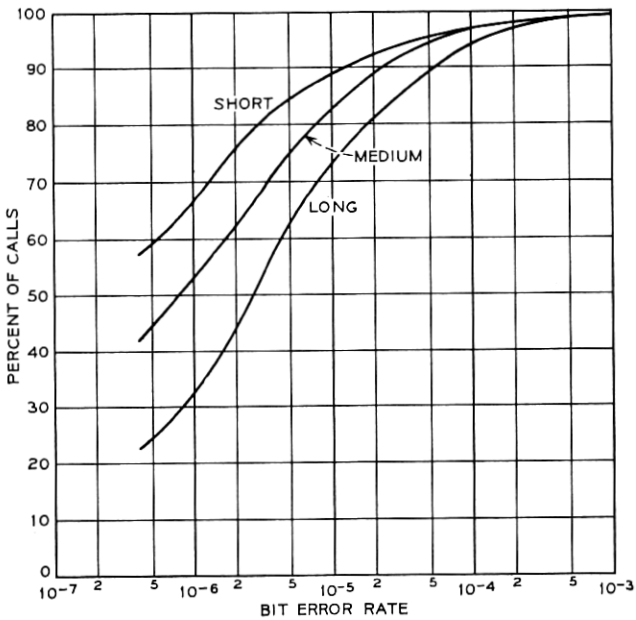

Fig. 3—Bit error rate distributions by mileage strata at 2000 b/s.

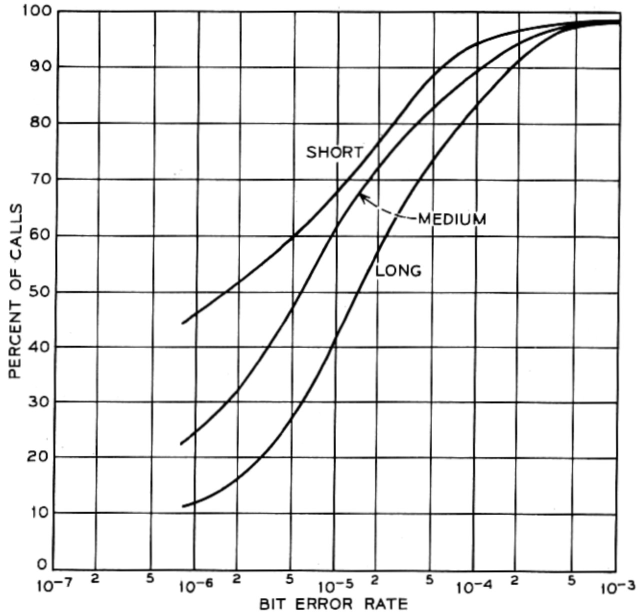

Fig. 4—Bit error rate distributions by mileage strata at 3600 b/s.

The means and 90 percent confidence intervals about the means for the error rate distributions are presented in Table III. Since the error rate distributions are skewed, the mean error rates are largely determined by the worst-case calls. For example, for all of the calls measured at 2000 b/s, 72 percent of the errors counted during the survey occurred on that 5 percent of the calls which had the poorest error rate. Similar results were obtained for the other data sets. For this reason the means fall above the 80th percentile and do not represent good measures of the locations of the distributions. The degradation of error rate performance with mileage seen in the relative positions of the CDFs is not shown by their means.

TABLE II—PERCENT OF ERROR FREE CALLS

Mileage Band	1200 b/s (30 min.)	2000 b/s (30 min.)	3600 b/s (20 min.)
Short	46	53	41
Medium	32	35	22
Long	24	18	10

Table III—Error Rate Means and Confidence Intervals

		Arithmetic		Logarithmic	
Data Rate b/s	Mileage Band	Mean Error Rate	90% Confidence Interval About Mean	Antilog of Mean Log Error Rate	90% Confidence Factor
1200	Short	5.8×10^{-5}	$\pm 5.6 \times 10^{-5}$	8.5×10^{-7}	1.5
	Medium	7.7×10^{-5}	$\pm 8.0 \times 10^{-5}$	1.3×10^{-6}	2.0
	Long	6.4×10^{-5}	$\pm 5.2 \times 10^{-5}$	2.8×10^{-6}	1.7
2000	Short	2.4×10^{-5}	$\pm 2.0 \times 10^{-5}$	8.9×10^{-7}	1.6
	Medium	1.2×10^{-5}	$\pm 8.8 \times 10^{-6}$	1.4×10^{-6}	2.0
	Long	2.1×10^{-5}	$\pm 8.4 \times 10^{-6}$	3.0×10^{-6}	1.7
3600	Short	5.4×10^{-5}	$\pm 6.1 \times 10^{-5}$	2.3×10^{-6}	3.0
	Medium	8.1×10^{-5}	$\pm 6.5 \times 10^{-5}$	5.3×10^{-6}	2.0
	Long	7.3×10^{-5}	$\pm 1.9 \times 10^{-5}$	1.3×10^{-5}	1.5

Because the error rate distributions are approximately log normal, means and confidence intervals have also been calculated for the log of the error rate. For the special case when the call was error free, the minimum error rate was assigned, i.e., one error per call. The antilogs of the result of this calculation are given in Table III. The confidence interval is represented as a factor, which when used to multiply and divide the logarithmic mean shown in Table III will result in the upper and lower confidence limits respectively. These means are closer to the median and are consistently larger with distance.

V. BURST AND BLOCK ERROR RATE PERFORMANCE

Errors on telephone channels tend to occur in bursts. To characterize this property, measures of error performance other than error rate are needed. In these results an error burst is defined to be a collection of one or more bits beginning and ending with an error and separated from neighboring bursts by 50 or more error free bits. The intent of this definition is to associate errors caused by a single event and dissociate errors caused by separate events and thus obtain a measure of the frequency of error causing events on a particular test call. Burst rate, then, is the number of bursts in a call divided by the number of bits transmitted. Discussion is given later on the use of the parameter of 50 bits for this purpose.

Block error rate is a parameter of interest because data messages are usually transmitted in a blocked format. Many data transmission systems reject blocks which contain bit errors and retransmit the entire block. Hence, the block error rate is often of greater practical significance than the bit error rate. A block in error is defined as a block containing one or more errors, or a carrier off indication, when a call is subdivided into contiguous blocks of a given size beginning with the first bit in a call. Block error rate is the probability of a block being received in error. The relationship between the bit and block error rates is accounted for by the burst nature of the channel.

Figures 5 through 8 present the CDFs of total burst and bit error rate and block error rate for block sizes of 100, 500, 1000, 5000 and 10000 bits for data rates of 1200, 2000, 3600 and 4800 b/s. These distributions were formed by averaging the distributions for short, medium, and long mileage strata assuming equal weight in each mileage category.

Averaging over the mileage bands is done here and in the remaining sections of this paper in order to obtain a more compact presentation. It is done when the effects of distance can be ascertained by reference

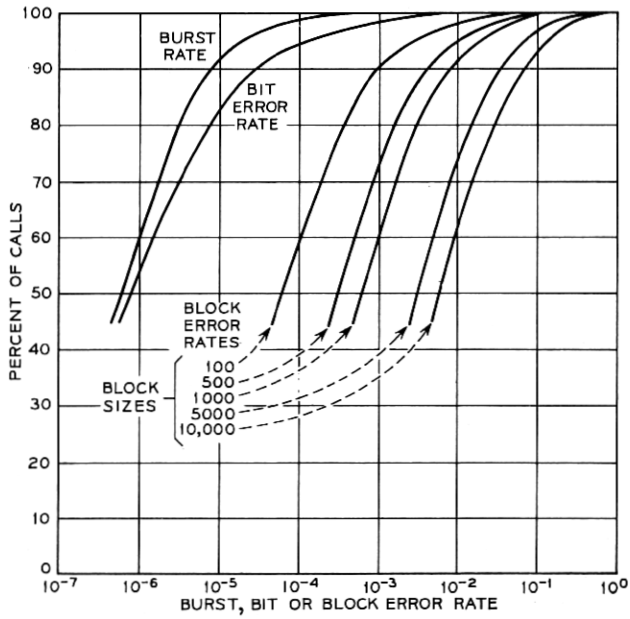

Fig. 5—Total burst, bit and block error rate distributions at 1200 b/s (Each mileage band weighted equally).

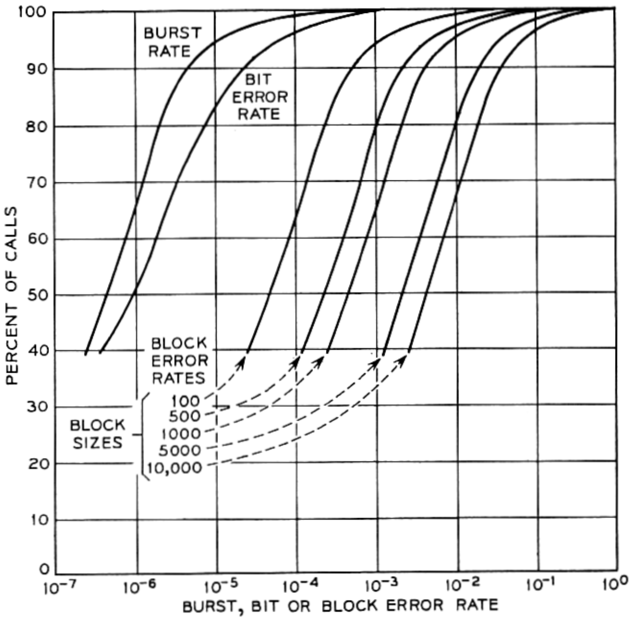

Fig. 6—Total burst, bit and block error rate distributions at 2000 b/s (Each mileage band weighted equally).

to an earlier result, or when the conclusions to be drawn are not strongly dependent on distance. For operation at 4800 b/s the results are presented in this fashion for a different reason. This data set was tested over a relatively small number of connections. Therefore, sufficient information was not available for an analysis by mileage band.

One method of combining the mileage band information would be according to the distribution of toll traffic on the Bell System Switched Network. The approximate percentages of toll traffic are 85, 11 and 4 percent in the short, medium, and long mileage strata respectively. If the distributions were combined in this way the characteristics of the short-haul calls would dominate, with the long-haul calls having little representation. In this paper, total performance is calculated by giving each mileage category equal weight and averaging the results for the three strata, making the result more meaningful for all mileages.

From Figs. 5 through 8, the burst nature of the channel can be seen in the separation between the distribution of burst and bit error rate.

It is noted that this separation generally increases with increasing error rate, indicating that calls with higher error rates tend to have more errors per burst. The effects of error bursts can also be observed by comparing the bit and block error rates. A measure of burstiness is the average number of errors per block in error. This may be estimated by multiplying the bit error rate by a given block size, then dividing by the block error rate. It has been calculated for 1000 bit blocks at the 80th percentile for all four data rates. At 1200 and 2000 b/s, the results are 2.6 and 3.5 errors per block in error respectively. For operation at 3600 and 4800 b/s, this number is approximately ten; the increase is largely due to the effect of the scrambler. As block size increases, the average number of errors per block in error increases slightly.

Another interesting observation that can be made from Figs. 5 through 8 is the relationship between the burst rate and block error rate distributions. It is noted that if the burst rate distribution is shifted to the right by the block size, it gives a good approximation to the block error rate distribution for that block size. This indicates

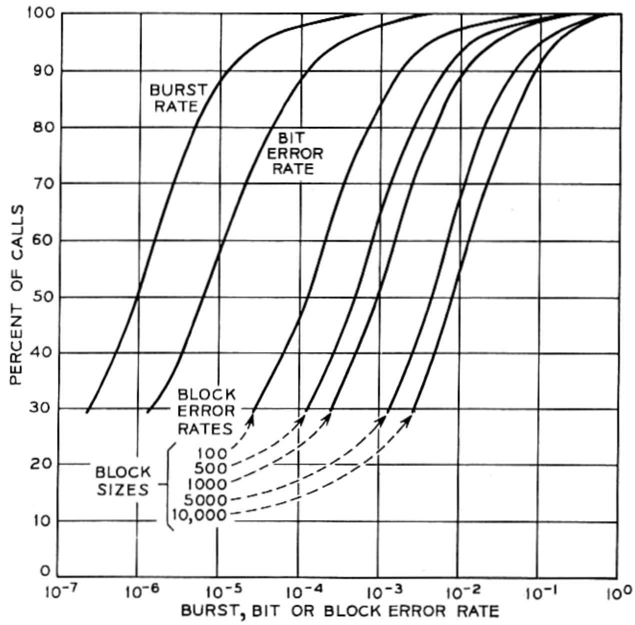

Fig. 7—Total burst, bit and block error rate distributions at 3600 b/s (Each mileage band weighted equally).

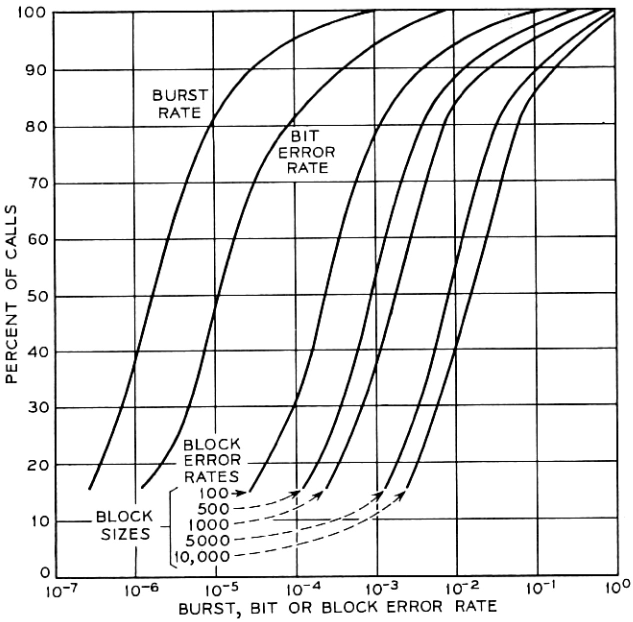

Fig. 8—Total burst, bit and block error rate distributions at 4800 b/s (Each mileage band weighted equally).

that the choice of 50 bits in the definition of a burst reasonably satisfies the intent of the definition.

On a mileage band basis the burst, bit and block error rate distributions maintain approximately the same relationships as for the total results given in this section. Therefore, a reasonable estimate may be obtained by mileage strata using Figs. 2, 3 and 4. To facilitate comparisons of bit and 1000-bit block error rate at the four speeds, Fig. 9 has been included.

VI. EFFECT OF CARRIER OFF INDICATIONS ON PERFORMANCE

Each of the data sets described in this paper is equipped with a carrier detector which indicates an ON condition during normal reception of data signals. An OFF indication is given in the absence of received signal energy. However, an OFF indication can also be caused by other severe line disturbances such as high amplitude impulse noise. Results for all three data sets indicate that the majority of carrier off indications were caused by disturbances other than loss of received line signal.

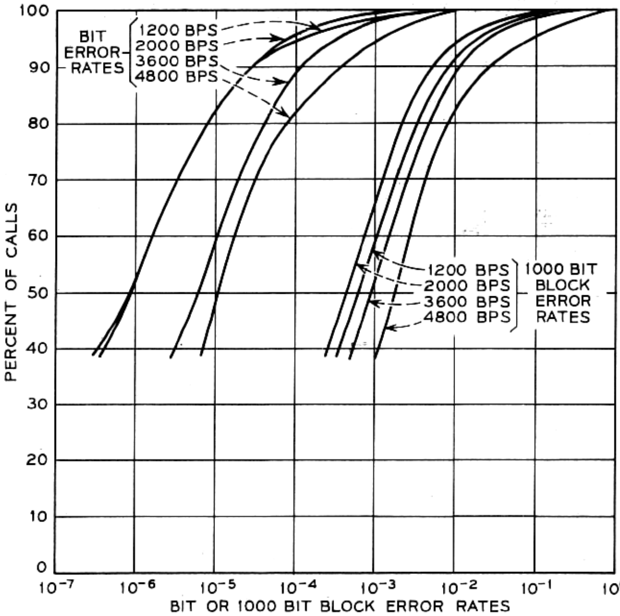

Fig. 9—Comparison of bit and 1000 bit block error rates. (Each mileage band weighted equally).

During a carrier off indication, the output of the data set is clamped to steady marking, thus forcing the error pattern to be an exact replica of the locally generated test word. All of the results presented earlier in the paper have included those errors. When they were removed and the bit and block error rate distributions recomputed, the curves were displaced upward by less than four percentage points.

Table IV gives the percentage of test calls which experienced carrier off indications. For the calls with one or more carrier off indications, the median call had three, two and one indications for the 1200,

TABLE IV—PERCENTAGE OF TEST CALLS WITH ONE OR MORE CARRIER FAILURE INDICATIONS

Mileage Band	1200 b/s	2000 b/s	3600 b/s
Short	7.0	9.1	14.3
Medium	7.9	14.8	7.2
Long	10.3	21.7	14.6

2000, and 3600 b/s data sets respectively. There were instances, however, where calls contained hundreds of carrier off indications.

The probability distributions of the duration of carrier off indications were computed for the three data sets. The results are contained in Fig. 10. Substantial differences can be seen between these distributions. These differences, as well as those shown between data sets in Table IV, are mainly due to differences in the design of the data sets.

VII. BURST PROPERTIES

This section discusses the characteristics of error bursts, based on the definition given earlier. The definition required an error free interval of 50 bits or more between bursts. Two measures of the size of error bursts have been calculated for the survey data. Burst weight is defined to be the number of errors in a burst and burst length is defined to be the number of bits in a burst. The probability distributions of these parameters are plotted in Figs. 11 and 12. The distributions have been computed by combining all of the test calls because burst characteristics did not appear to be closely related to mileage.

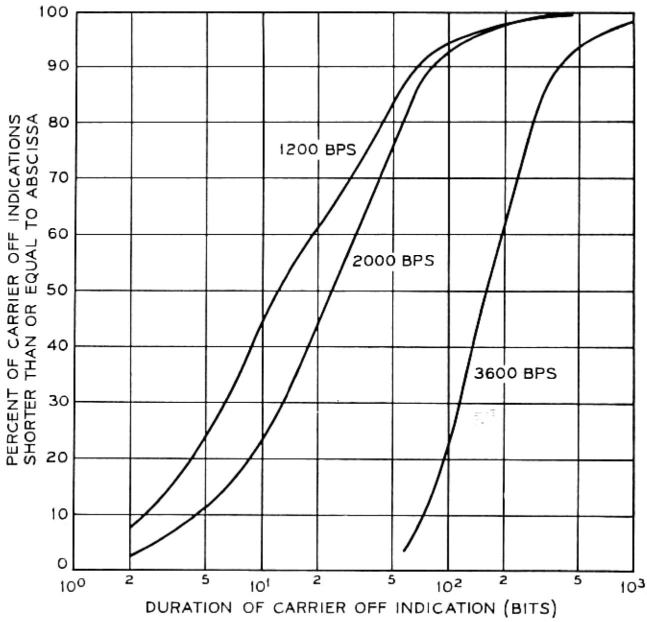

Fig. 10—Distribution of durations of carrier off indications.

The properties of bursts which occurred when the carrier indication was on are presented here. The characteristics of errors occurring during carrier off indications were discussed in the preceding section.

The difference in bit rates and signaling formats for the three data sets contribute to the differences which are evident in these curves. From Figs. 11 and 12, it can be seen that small bursts for the 2000 b/s data set tend to be slightly larger than small bursts for the 1200 b/s set. This may be due to the use of differential encoding. The effect is overcome when bursts of any appreciable size are encountered.

The scrambler used in the 3600 b/s data set causes burst structures considerably different from the lower speed sets. To estimate what the distribution of burst weight would be for the high-speed set with no scrambler, the scale of the abscissa should be divided by three. When this is done for the curve in Fig. 11, it is very similar to those of the other data sets. To remove the effect of the scrambler on burst length, a different procedure must be used. There is a residual effect in any burst of 23 bits while the descrambling shift register clears, thus an estimate of the unscrambled burst length distribution can

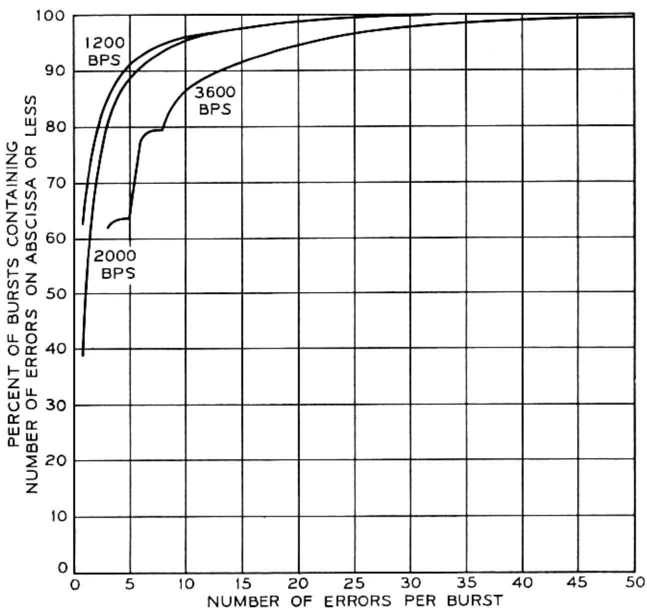

Fig. 11—Burst weight distributions.

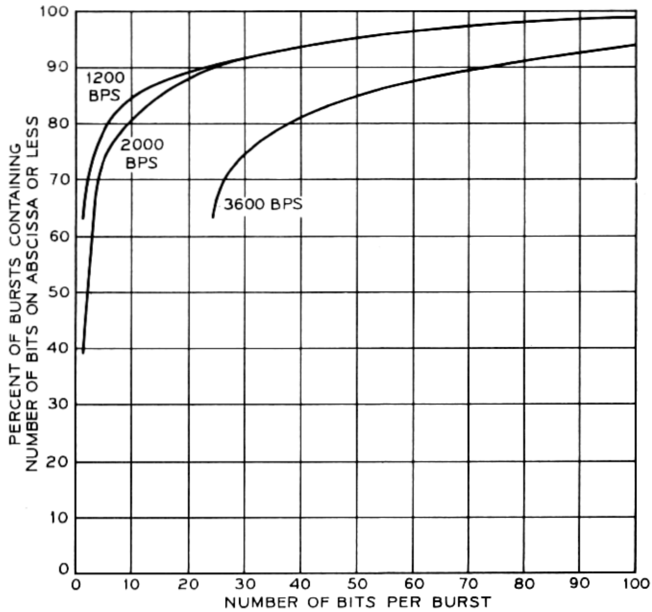

Fig. 12—Burst length distributions.

be obtained by shifting the curve 23 bits to the left. Once again the curve obtained is similar to those of the other data sets.

The burst weight distributions given in Fig. 11 may tend to obscure bursts with many errors because of the frequency of small bursts. Thus, for each test call, the number of errors in the largest burst has been calculated. Figure 13 presents the CDF of the percent of calls versus maximum burst weight per call for the three data rates. Note from this figure that 80 percent of the calls for the 1200 and 2000 b/s modems have maximum burst weights of less than three and six errors respectively. For 3600 b/s operation, the maximum weight is approximately 25 at this point. This increase is mainly attributable to the error tripling effect of the scrambler.

VIII. PROBABILITY OF M ERRORS IN A BLOCK OF N BITS

The number of errors per block is a measure which is useful for evaluation of error control procedures using block transmission. The probability distributions for m or more errors in a block of n bits $[P(\geqq m,\, n)]^2$ are presented in Figs. 14, 15, and 16 for data rates of 1200, 2000, and 3600 b/s.

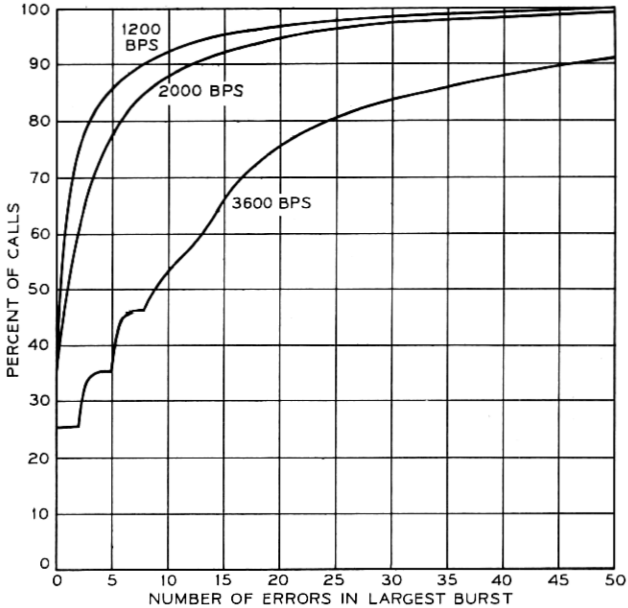

Fig. 13—Distributions of the maximum burst weight per call.

Since the results are not strongly related to distance, these curves were calculated by averaging over all of the calls. Blocks which contained carrier off indications were not included in these calculations.

These curves indicate the overall similarity of the three sets as measured by the block error probability [i.e., $P(\geqq 1, n)$]. The 2000 b/s data set has the lowest probability of a block error and the 3600 b/s set the highest; they differ by approximately a factor of two.

Because the 2000 b/s and 3600 b/s data sets tend to have relatively more multiple errors, the probabilities, $[P(\geqq m, n)]$, for the 1200 b/s set are smaller than for the other two sets, for m greater than one.

IX. GAP LENGTH DISTRIBUTIONS

The probability distributions of the number of good bits between errors (gap length distribution) provide additional insight into the error process. They are presented in Figs. 17, 18 and 19 for the 1200, 2000, and 3600 b/s data sets. All of the test calls have been used without regard to mileage band. Bits which coincided with a carrier off indication were removed. Since instances where carrier off indications

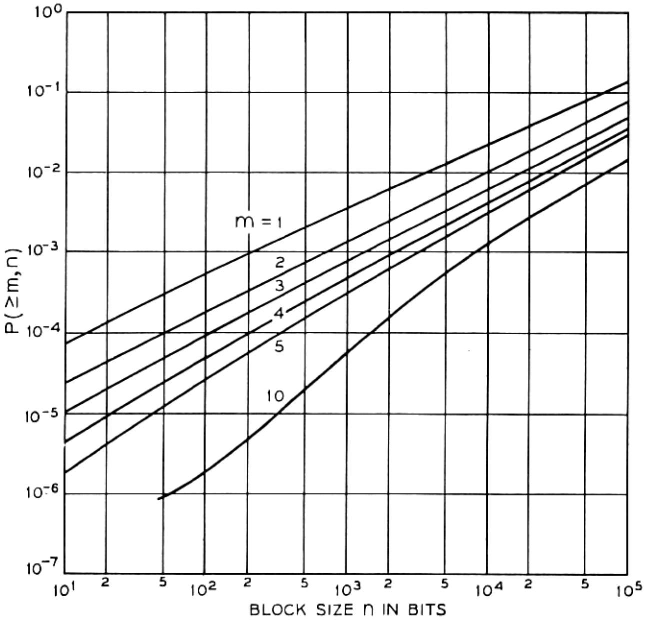

Fig. 14—Probability of m or more errors in a block of size n [$P(\geqq m, n)$] at 1200 b/s.

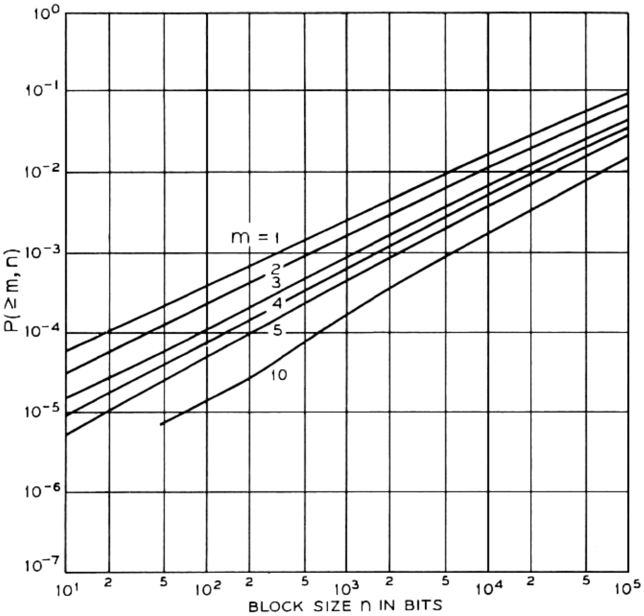

Fig. 15—Probability of m or more errors in a block of size n [$P(\geqq m, n)$] at 2000 b/s.

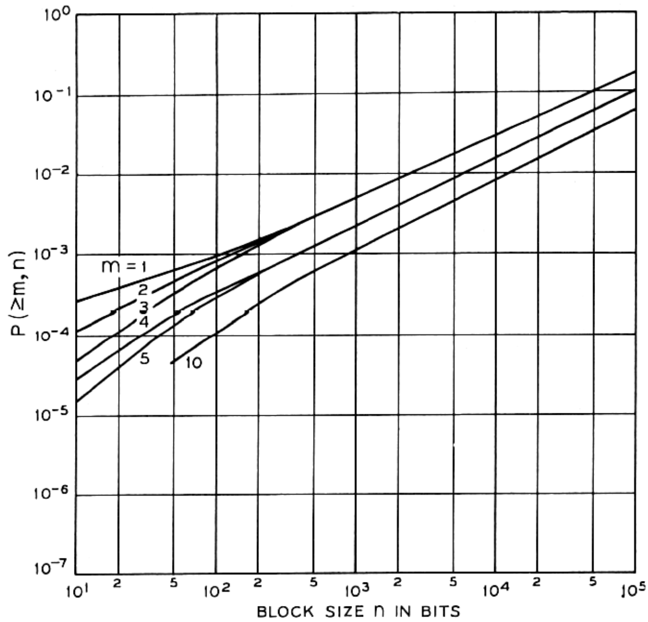

Fig. 16—Probability of m or more errors in a block of size n [$P(\geqq m, n)$] at 3600 b/s.

are not preceded by errors are rare, this culling should have an effect on the number of very short gaps but not on the number of long gaps.

Four curves are presented in each of these figures. The curves labeled Pooled Bit Error Gap Distribution were computed by pooling all of the test calls together and calculating the gap length distribution of the result. That is, for each data set, the pooled distribution contains all gaps from all calls. A call with a poor error rate contributes many more gaps than one with a good error rate. The pooled gap length distribution may be a reasonable estimate of the overall gap length distribution if it can be assumed that the error sequences of the individual test calls are segments of one call of long duration. If this assumption about the error process is not valid, then the pooled estimate may be unreasonable since in it, equal weight is assigned to each gap, causing calls with a large number of errors to contribute the major share of the information. In fact, for 2000 b/s operation one call accounted for approximately 11 percent of the errors made in the entire survey. One can be fairly certain that the pooled distribution will not be very different from the gap length distribution of that call.

In order to assign equal weight to each call in the sample, the gap

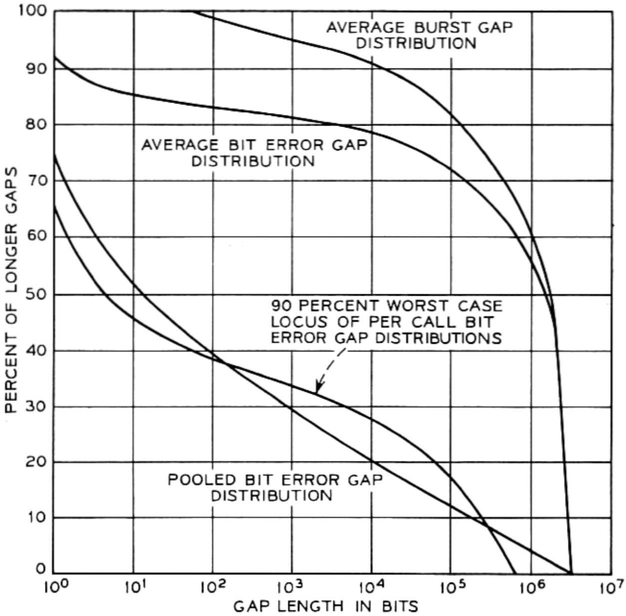

Fig. 17—Total gap length distributions at 1200 b/s.

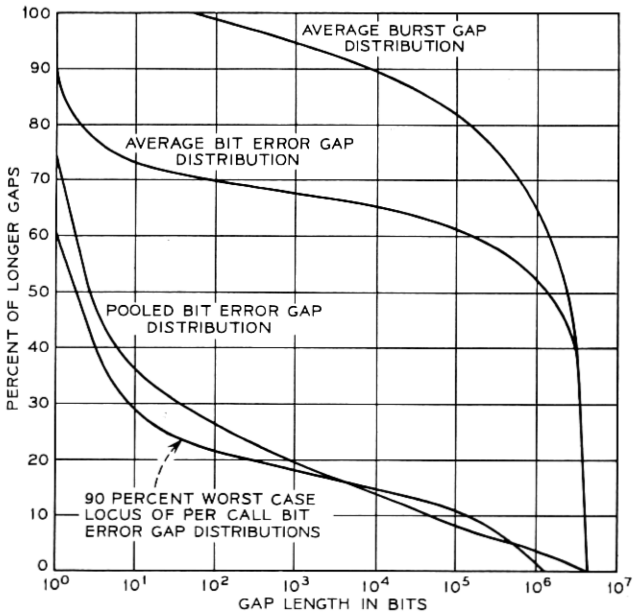

Fig. 18—Total gap length distributions at 2000 b/s.

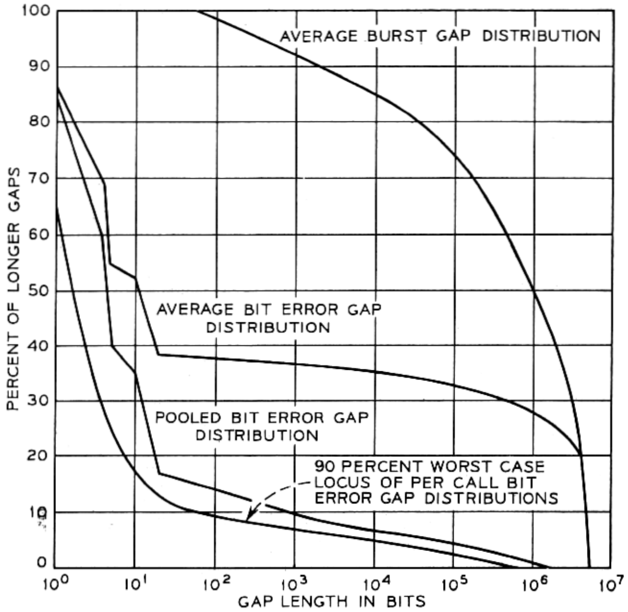

Fig. 19—Total gap length distributions at 3600 b/s.

length distribution was computed for each call and the results averaged to obtain an overall distribution. This is done by summing the per call ordinates for each gap length and dividing by the number of calls. Using this method, no one call can determine the shape of the distribution. The curves labeled Average Bit Error Gap Distribution in Figs. 17, 18 and 19 have been computed in this way.

The product limit[10] method of estimation has been used to calculate the gap length distributions. In this method the observed gaps are used to compute the conditional probability

$$P\{\text{Gap} \geqq g \mid \text{Gap} \geqq g - 1\} = \frac{P\{\text{Gap} \geqq g\}}{P\{\text{Gap} \geqq g - 1\}} \tag{1}$$

for a number of cell sizes ranging from 0 (consecutive errors) to the test call length in bits (error free call). Since

$$P\{\text{Gap} \geqq 0\} = 1,$$

the gap length distribution is computed as follows

$$P\{\text{Gap} \geqq g \mid \text{Gap} \geqq g - 1\} \cdot P\{\text{Gap} \geqq g - 1\} = P\{\text{Gap} \geqq g\}.$$

The advantage of using this method is that the gap which precedes the first error and that which follows the final error in the test call are used in equation (1) as long as they contain information, that is, up to their length. At this point they disappear from both the numerator and the denominator simultaneously.

The 90 percent worst-case distribution shown in Figs. 17, 18 and 19 is the locus of points such that for each gap length the ordinates of 90 percent of the calls lie above that point. Note that for all three data sets, the pooled distribution falls roughly at this 90 percent worst case locus. Since, for each data set, between 80 and 90 percent of the calls have error rates better than the average error rate, the effect of pooling on determining the gap length distribution estimate is approximately the same as its effect on the calculation of average error rate. For the 3600 b/s data set, the mean is approximately the 80 percent point and for this data set the pooled distribution is uniformly above the 90 percent worst-case locus.

A comparison of the gap length distribution of the different types of data sets is complicated by the fact that the sets use different transmission techniques and different speeds. The 2000 b/s modem is a differentially encoded four-phase set which transmits dibits. The 1200 b/s set is an FM set which transmits a single bit per signaling element. Hence, one might expect more short gaps for the higher speed modem. As shown by the gap length distributions, this in fact occurs. For the 3600 b/s data set, gaps of length 17 and 4 are common since those are the bit spacings on the descrambler shift register.

The relative flatness of all of the gap length distributions following the initial decline indicates a relative insensitivity to the critical length of 50 bits used in the burst definition. This flatness also gives insight into the fact that the spacings between the block error rate curves given in Figs. 5, 6 and 7 are approximately equal to the ratios of the block sizes. The same point can be observed in the linearity of the $P(\geqq m, n)$ curves given in Figs. 14, 15 and 16.

Since every gap of length 50 or longer separates bursts and only gaps of length 50 or longer do so, the distribution of bits between bursts for each call can be derived from the gap length distribution by simply renormalizing the curve for gaps of size 50 and greater. This has been done for the survey calls and the resulting curves averaged to arrive at the average burst gap distributions also shown in Figs. 17, 18 and 19. The pooled burst gap distribution can be obtained by renormalizing the pooled bit error gap distribution.

Figure 20 contains the average gap length distributions for the

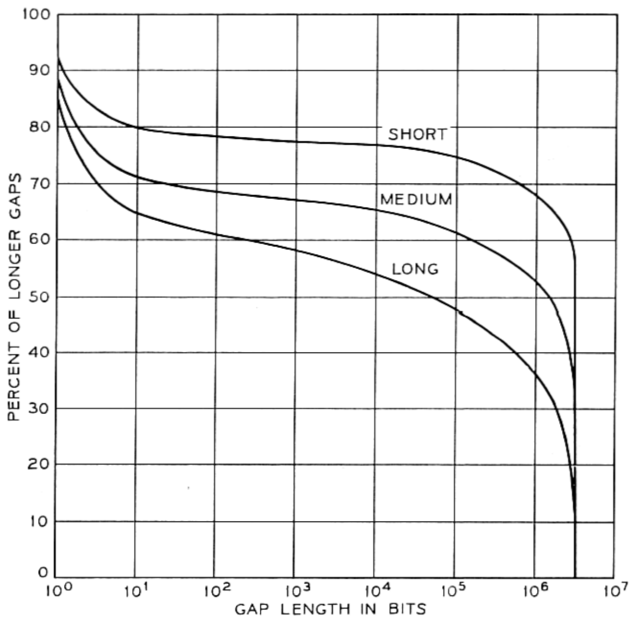

Fig. 20—Gap length distributions by mileage strata at 2000 b/s.

2000 b/s data set for the three mileage bands. As shown in this figure the additional transmission impairments encountered on long-haul calls manifest themselves throughout the range of the gap length distribution. The same relationship was observed for the other two sets, but in different degrees. The 1200 b/s set showed less sensitivity to distance and the 3600 b/s set showed greater sensitivity. Since 1200 b/s operation uses the channel least efficiently in terms of bit speed, it could be argued that it should have the greatest margin to error and should therefore be less sensitive to the additional impairments introduced when the transmission distance is increased.

For all three data sets, the gap length distribution of medium haul calls is very close to the overall average distribution.

X. EFFECT OF SIMULATED LOOPS ON THE 1200 AND 2000 B/S DATA SETS

The 1200 and 2000 b/s data sets were also tested using simulated loop pairs to obtain information on the effect of amplitude and phase distortions introduced by the loop plant. The results indicate that the additional impairment added with the simulated loops had little influence on the performance of the data sets. For the distributions of burst, bit and block error rates, performance with the loop was slightly better than without. For the 1200 b/s data set, performance with the loops resulted in a general upward shift of the distributions of less than four percent. At 2000 b/s this shift was approximately two percent. From this result it appears that the compromise equalizers of both data sets more nearly equalize the channel with loops. The major change in the analog channel characteristic caused by the addition of the loops is an increase in the loss frequency slope. The result obtained above may indicate that the 1200 b/s data set is more sensitive to this impairment than the 2000 b/s data set.

XI. EFFECTS OF EXCLUDING SXS SWITCHING OFFICES FROM THE SAMPLE

As discussed earlier two SXS offices which were initially selected, were not included in the sample used to estimate high-speed data transmission performance. These offices exhibited excessive amounts of high-level impulse noise which was mainly attributed to equipment used to select outgoing trunks. Based on the impulse noise pretest, three other offices having similar equipment were not excluded from the sample. To determine the effect of these three offices on the overall results, a subclass analysis was performed excluding calls which encountered this equipment. Figure 21 shows the bit error rate and 1000-bit block error rate at 2000 b/s for the total distributions of the overall sample and the sample excluding calls through this equipment. In performing this analysis, 21 percent of the test calls were excluded. From Fig. 21 it can be observed that the error rate distribution with this exclusion shows an improvement of approximately a factor of two. The block error rates differ by a smaller factor. At 1200 and 3600 b/s, the relationship between the distributions is similar.

Another analysis was performed excluding all calls which encountered SXS equipment at the primary or secondary sites. This resulted in an exclusion of 58 percent of the test calls. The resulting distributions show no additional improvement over those obtained above.

XII. ANALYSIS OF ERROR CAUSING TRANSIENTS AT 2000 B/S

The process which results in bit errors involves a combination of static impairments and transient phenomena acting on the data set line signal. In the absence of other factors, a data set can generally withstand fairly large amounts of impairments such as loss slope or delay distortion without producing errors. Thus, errors can be viewed as caused by transients such as impulse noise and phase changes, where

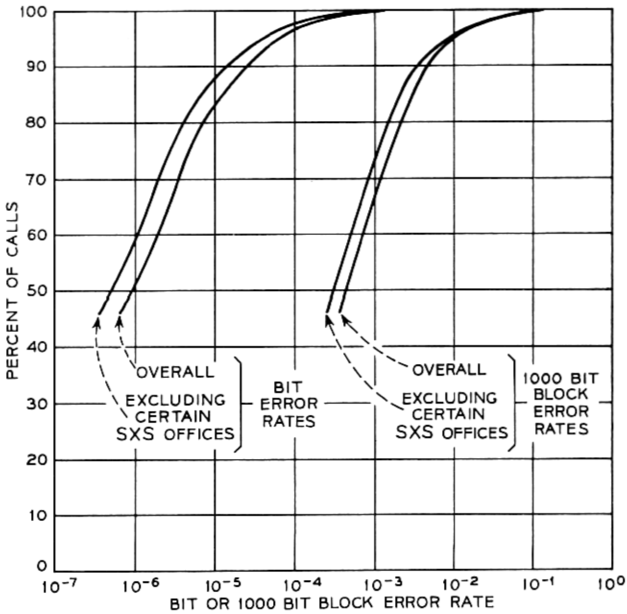

Fig. 21—The effect of excluding certain SXS offices on bit and block error rate at 2000 b/s.

the static impairments determine the sensitivity to these transients. Samples of the 2000 b/s line signal were recorded at six of the twelve receive sites to obtain information on the types of transient disturbances causing errors for this data set.

An analog to digital converter was used to obtain samples of the line signal entering the Data Set 201 receiver. When the received bit stream contained an error, a 50 ms sample of the line signal containing the error causing disturbance was stored for later analysis. No further samples were taken for approximately ten seconds. After this interval, another segment of line signal was stored for comparison with the first. The error causing transient had usually ended before the second segment was recorded.

This information has been analyzed, and major error causing disturbances have been separated into four categories: Short Transients, Additive Signals, Amplitude Changes and Phase Changes.

Short transients are defined arbitrarily as any disturbances of the line signal lasting for 4 ms or less. Transients observed affected both the amplitude and phase of the signal. The most common type of short transient observed was additive impulse noise. However, transients which appeared to affect only the phase of the line signal were also common, especially in the long mileage category. Examples of an additive impulse and a phase transient are given in Figs. 22a and b. In Fig. 22a, the top trace is the line signal segment which contains the error causing transient; next is the reference version of the same line signal segment. The third trace is the difference between the upper two traces. The bottom trace is the bit pattern with the error bits indicated. This pattern is displaced to the right by approximately 2 ms from the line signal disturbance due to propagation delay through the data set receiver. Figure 22b has the same format, but the top two traces are superimposed. This disturbance caused one error which is not indicated on the figure, since it occurred beyond the last bit shown.

A second category of observed disturbances, additive signals, involved the addition of an extraneous waveform to the data signal. By the definition employed here, these additives lasted for more than 4 ms. Some causes of these disturbances were speech signals or tones crosstalking into the test line, or increases in noise level.

Data signal amplitude changes were observed where the resulting level lasted for more than 4 ms. Included in this category were occurrences of loss of line signal, generally referred to as dropouts. An example of an observed dropout is given in Fig. 22c.

Phase changes were also observed; the resulting phase differed from the original phase for more than 4 ms. Typically the phase change occurred in less than 1 ms. An example is shown in Fig. 22d. Other phase changes took place more gradually as the phase appeared to rotate slowly.

Categorizing the line signal samples allows some determination of the relative frequency of occurrence of these disturbances and their effects on error performance. Table V lists the percent of observed bit errors which were caused by the various categories of transient phenomena. It also lists the percent of observed line signal disturbances of each type, and the average number of errors per disturbance for each category. So that the results would not be dominated by a few calls with relatively poor performance, this table only includes calls with error rates better than 10^{-4}. Causes of errors for calls with error rates poorer than 10^{-4} are discussed in the next section.

At this point, it should be emphasized that these results are based on the observation of line signal disturbances resulting in errors incurred using a Data Set 201. Although the categorization is done on

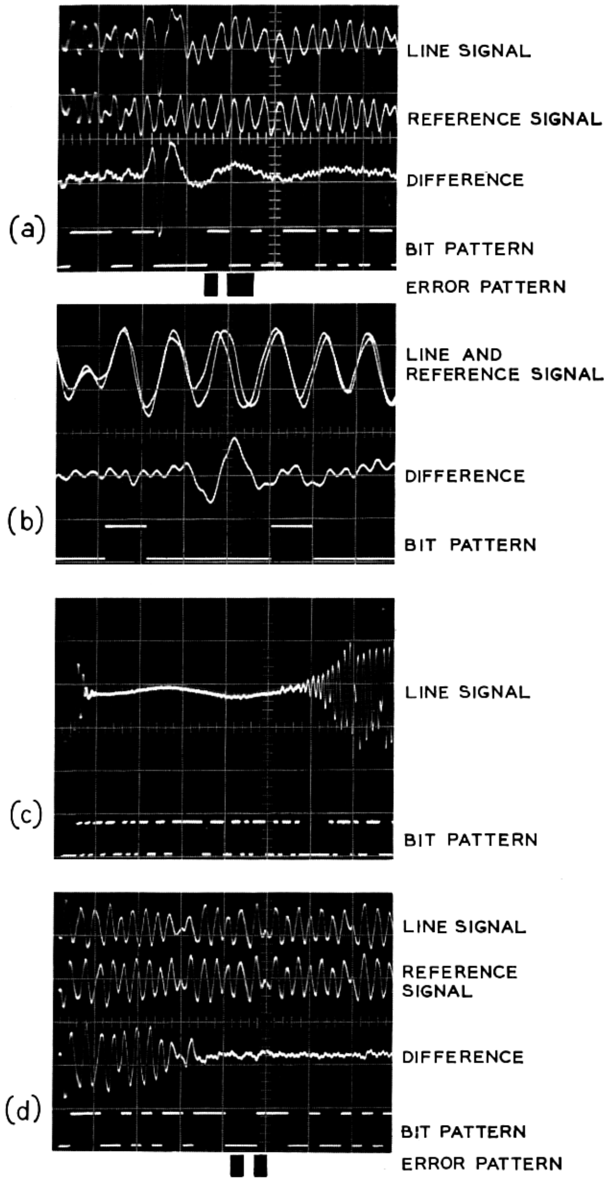

Fig. 22—Examples of observed transient disturbances. (a) Additive impulse (2 ms/div). (b) Phase transient (0.5 ms/div). (c) Dropout (5 ms/div). (d) Phase change (2 ms/div).

TABLE V—OBSERVED CAUSES OF ERRORS FOR OPERATION AT 2000 b/s

Type of Disturbance	Percent of Errors	Percent of Line Signal Disturbances	Average Number of Errors Per Disturbance
Short Transients	63	79	3
Additive Signals	25	6	17
Amplitude Changes	5	4	8
Phase Changes	7	11	2

the basis of transient disturbances, static impairments have a role in determining these percentages. Also, the results are based on a portion of all errors experienced during the survey. Thus, the results are useful to indicate trends, but caution must be used in extending these results to other modem types or to the performance of Bell System data services in general.

Additional information is obtained by analyzing the line signal samples on a mileage band basis. Disturbances such as phase changes and phase transients accounted for approximately three percent of the bit errors observed in the short mileage band, but accounted for approximately 26 percent of the observed errors in the long mileage band. On the other hand, impulse noise is a significant cause of errors in all mileage strata. Short transients identified as additive impulses accounted for 45 percent of all the bit errors observed.

Results presented earlier in this paper have given information on the occurrences of carrier off indications on the data sets tested. Carrier off indications are usually thought of as being the result of line signal interruptions or dropouts. However, analysis of the line signal samples for the Data Set 201 indicates that 25 percent of the observed carrier off indications were caused by dropouts. The remaining 75 percent were caused by severe line signal disturbances such as high-level additive impulse noise.

12.1 *Analysis of 2000 b/s Calls With Error Performance Poorer Than 10^{-4}*

Although only 3.5 percent of the connections (20 calls) on which the 2000 b/s modem was tested had error rates poorer than 10^{-4}, 66 percent of all errors made by the Data Set 201 occurred on these calls. These connections were well distributed throughout the survey with no more than two such calls between any primary-secondary pair, and no primary site with more than three.

It was determined that the principal source of errors in more than half of these calls was additive impulse noise and other additive signals. Line signal dropouts and the various phase related phenomena mentioned earlier also caused several calls to have error rates poorer than 10^{-4}.

XIII. COMPARISONS WITH PREVIOUS SURVEYS

The results presented in this paper show a considerable improvement in error performance compared with the results of the 1959 Alexander, Gryb, Nast Survey.[1] For example, results of the present survey show that for operation at 1200 b/s 82 percent of the calls have error rates of 10^{-5} or better, for equal weighting in the three mileage bands. The AGN Survey reported 63 percent of their test calls achieving this performance level for operation at the same data rate. It should be pointed out, however, that a number of differences in the sampling plans and testing procedures exist between the two surveys precluding a detailed comparison of results. For example, the present survey used a sampling plan based on toll traffic which gave a wide distribution of test site locations, whereas the AGN Survey concentrated more on backbone routes. Also all test calls in the present survey were dialed. In the earlier survey a substantial number of calls were operator handled. Mileage categories were defined differently for the two surveys. Loops were not used in the present survey but were used by AGN. Also, the transmit level was −12 dBm at the serving central office for the present survey. It was −6 dBm at the same point for the AGN Survey.

Improvements in error performance of approximately the same size as those noted at 1200 b/s can be shown by comparing the results presented in this paper for 2000 b/s operation with results from the 1962 Townsend-Watts[2] field measurement program. Again, differences in sampling plan and test procedures do not allow precise comparisons.

For operation at 3600 b/s, bit error rate results presented in this paper are very similar to those obtained from the 1965 Farrow-Holzman[3] field measurements, even though the data set used in the 1969-70 Connection Survey employed a data scrambler, and the data set used in the earlier survey did not.

XIV. SUMMARY AND CONCLUSIONS

This paper has reported estimates of data transmission error performance for operation at 1200, 2000, 3600 and 4800 b/s based on measurements made as part of the 1969-70 Connection Survey. Toll traffic was used as the basis for the sampling plan which resulted in the selection of approximately 600 dialed toll connections between geographically dispersed Bell System local switching offices.

A substantial improvement in performance has been noted in comparison with previous surveys.

Performance estimates have been based on the following measures: bit error rate, burst rate, block error probabilities and distribution of time between errors. Information has also been given on the structure of error bursts and the duration of data set carrier off indications.

A general tendency for performance to degrade with transmission distance has been noted. The magnitude of the degradation is not the same for all measures of performance.

In comparing the performance of the three data sets it must be remembered that they employ different transmission formats, modulation techniques, and widely differing bit rates. Because of transmission techniques used in the Data Set 203 it tends to have more errors per burst than either of the other sets. For this reason bit error performance at 3600 and 4800 b/s does not compare as well to bit error performance at 1200 and 2000 b/s as does block error performance at the higher speeds to block error performance at the lower speeds.

Line signal samples containing transient disturbances which resulted in bit errors for the 2000 b/s data set were recorded. The results indicate that impulse noise accounted for a large percentage of the observed errors. A strong relationship between transmission distance and the percentage of phase related disturbances was observed.

XV. ACKNOWLEDGMENTS

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REFERENCES

1. Alexander, A. A., Gryb, R. M., and Nast, D. W., "Capabilities of the Telephone Network for Data Transmission," B.S.T.J., *39,* No. 3 (May 1960), pp. 431–476.
2. Elliott, E. O., "A Model of the Switched Telephone Network for Data Communications," B.S.T.J., *44,* No. 1 (January 1965), pp. 89–109.

3. Morris, R., "Further Analysis of Errors Reported in Capabilities of the Telephone Network for Data Transmission," B.S.T.J., *41,* No. 4 (July 1962), pp. 1399–1414.
4. Townsend, R. L., and Watts, R. N., "Effectiveness of Error Control in Data Communications Over the Switched Telephone Network," B.S.T.J., *43,* No. 6 (November 1964), pp. 2611–2638.
5. Farrow, C. W., and Holzman, L. N., "Nationwide Field Trial Performance of a Multilevel Vestigial Sideband Data Terminal for Switched Network Voice Channels," Conference Record, 1968 IEEE Conf. Commun., June 12–14, Philadelphia, Pennsylvania, p. 782.
6. Duffy, F. P., and Thatcher, T. W., Jr., "1969–70 Connection Survey: Analog Transmission Performance on the Switched Telecommunications Network," B.S.T.J., this issue, pp. 1311–1347.
7. Fleming, H. C., and Hutchinson, R. M., Jr., "1969–70 Connection Survey: Low-Speed Data Transmission Performance on the Switched Telecommunications Network," B.S.T.J., this issue, pp. 1385–1405.
8. Data Communications Using the Switched Telecommunications Network, Bell System Data Communications Technical Reference, AT&TCo., August 1970.
9. Gresh, P. A., "Physical and Transmission Characteristics of Customer Loop Plant," B.S.T.J., *48,* No. 10 (December 1969), pp. 3337–3385.
10. Kaplan, E. L., and Meier, P., "Nonparametric Estimation from Incomplete Observations," J. Amer. Stat. Assn., *53,* June 1958, pp. 457–481.