NBS TECHNICAL NOTE 779

Data Communications System Throughput Performance Using High Speed Terminals on the Dial Telephone Network

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DATA COMMUNICATIONS SYSTEM THROUGHPUT PERFORMANCE USING HIGH SPEED TERMINALS ON THE DIAL TELEPHONE NETWORK

Dana S. Grubb

Throughput performance of high speed data terminals using the dial telephone network is calculated for signaling rate of 1200 to 4800 bits per second using the ANSI X3.28-1971 control procedures and measured in terms of the proposed ANSI standard TRIB described in X3S35/80. The performance calculations are shown graphically with TRIB as a function of block length, error rates of the telephone connection, signaling rate and telephone line delays. Error rates are based on a published survey involving several hundred telephone connections to geographically distributed parts of the United States.

Key Words: Data communications; modems; terminals; throughput; TRIB.

1. INTRODUCTION

The rapidly increasing use of terminals with high data rates on the dial telephone network indicates the need to evaluate their performance in terms of standard criteria. This report shows the calculated data throughput of toll calls on the dial telephone network in terms of the proposed ANSI criteria of TRIB (Transfer Rate of Information Bits) described in X3S35/80[1/] (X3.44 if adopted) with terminals using data modems in the 1200 to 4800 bit per second range. The use of the ANSI X3.28-1971[2/] control procedures is assumed. The error rates used are based on published data for the dial telephone network.

This report is an interim publication to be followed by reports covering the throughput and residual error rate performance of data communications systems using data rates to 9600 bits per second and including proposed higher level control procedures.

2. TRIB

TRIB is defined in the proposed ANSI standard as "the ratio of the number of Information Bits accepted by the receiving Terminal Configuration during a single Information Transfer Phase (Phase 3) to the duration of that Information Transfer Phase. TRIB is expressed in bits per second.

Information bits are all of the bits contained in information characters, except those used for parity and as start-stop bits. The information characters are those in the graphic subset of USASCII, which are transmitted as the message text, except for those characters used for control or affecting the format. Characters used in the message heading are not considered to be information characters.

The information transfer phase begins with the transfer of a SYN (synchronizing) character, a SOH (start of heading) character, or a STX (start of text) character. The phase is ended with the transfer of an EOT (end of transmission) character or DLE EOT (mandatory disconnect) character sequence. For more detailed information on TRIB see references 1 and 3.

For purposes of performance evaluation it is helpful to consider TRIB on a block basis. This is a valid simplification and TRIB is defined in this report as the number of information bits per block divided by the product of the time per block and the ratio of the number of transmitted blocks to the number of accepted blocks.

3. ANSI X3.28 CONTROL PROCEDURES

The X3.28 control procedures[2/] may be used with either synchronous or asynchronous systems. The 1200 BPS (bits per second) modem is an asynchronous modem, while the 2000, 3600 and 4800 BPS modems are synchronous modems.

The X3.28 control procedures provide several different modes of operation including: one-way-only and two-way-alternate, point-to-point and multi-point connections, switched and non-switched networks, with and without station identification, with and without message blocking, with and without replies, single and alternating acknowledgments, with and without longitudinal checking and other features. This report assumes subcategory 2.1 for point-to-point, two-way-alternate operation on a switched network without station identification. This report also assumes the complementary subcategory B1 for message blocking with longitudinal checking, retransmission of unacceptable blocks and single character acknowledgment. This combination of subcategories provides for operation on the dial telephone network with both vertical and longitudinal checking.

The X3.28 control procedures for subcategory 2.1 provide for breaking each message into one or more blocks, so that the number of bits per transmission may be limited. This permits selecting the number of bits per transmission block for optimum TRIB. Blocks with less than the optimum number of bits have a reduced TRIB due to the time spent reversing the direction of transmission and sending the reply. Blocks with more than the optimum number of bits per block have such a high probability of a block containing one or more error bits that too much time is spent retransmitting the blocks. The optimum number of bits depends upon several factors and will vary as these factors vary.

The first block of each message is defined by X3.28 as beginning with a heading. The number of bits used in the heading and the length of the following message will vary with systems. A typical system might have a 7-character heading and a 4200-character message. In such a case the heading comprises .166 percent of the total message and is negligible. In this report the time required to transmit the heading will not be considered in the calculation of TRIB.

With synchronous modems each block and each reply must be preceded by SYN (synchronizing) characters, so that the receiving terminal may achieve synchronization. In this report 4 SYN characters are assumed for both the message blocks and the replies, as this is an adequate number for most systems. With asynchronous modems no SYN characters are needed, as the start and stop bits for each character provide the necessary synchronization for the receiving terminal.

In the first block of each message an SOH (start of heading) character precedes the heading characters. After the heading characters, an STX (start of text) character denotes the end of the heading and the beginning of the text. At the end of each block an ETB (end of transmission block) character denotes the end of the block. It is immediately followed by the BCC (block check character) character containing the longitudinal parity bits. The reply consists of either an ACK (acknowledgment) character denoting that the block was accepted by the receiving terminal or a NAK (negative acknowledge) character denoting that the block was not accepted by the receiving terminal. Subsequent blocks of the message begin with an STX character. At the end of the last block of the message an ETX (end of text) character is sent instead of the ETB character.

Therefore, the 1200 BPS asynchronous modem will be assumed to use 3 control characters (STX, ETB or ETX, and BCC) per message block and 1 reply character (ACK or NAK). The 2000, 3600 and 4800 BPS synchronous modems will be assumed to use 7 control characters (4 SYN, STX, ETB or ETX, and BCC) per message block and 5 reply characters (4 SYN and ACK or NAK).

4. DATA ON ERROR RATES

The error rate data used in this report is from the 1969-70 Connection Survey listed in references 4 and 5.

In this survey, four types of modems were used for toll calls on the dial telephone network at modem speeds of 1200, 2000, 3600 and 4800 BPS. The connections were made between telephone end offices in widely distributed cities of the United States and Canada, with 98 different end office locations used for transmitting and 12 for receiving. These were chosen by statistical sampling techniques from the approximately 15,000 possible end office choices. The wide geographic dispersion of the end offices ensured the inclusion of calls from relatively nearby end offices to those almost three thousand miles away.

The 1200 and 2000 bit per second modems were each tested with over 500 calls of 30 minutes duration each. The 3600 and 4800 bit per second modems were tested with 277 and 130 calls, respectively, and a call duration of 20 minutes each. For additional information on this survey see reference 6.

5. MODEMS

The 1200 BPS modems use a design with frequency shift keying that is typical for modems in this bit rate class. The 2000 BPS modems use a design with four-level phase shift keying that is typical of their bit rate class. The 3600 and 4800 BPS modems are the same basic modem with minor modifications for the bit rate desired. They use a design with multilevel vestigial sideband amplitude modulation. There is more variation between modem designs in these classes.

The interblock delays in a data communications system depend to a large extent upon the modem design used. For modems up to 2400 BPS the design usually permits reversing the direction of transmission and sending the reply at the normal transmission rate. In this case the delay between the end of a message block and the beginning of a reply is the sum of the transmission delay (several milliseconds in most cases) and the time required for the telephone line to permit transmission in the reverse direction. On short distance calls it is desirable to wait about .05 seconds for echoes to subside. On longer distance calls the telephone companies often use echo suppressors to reduce objectionable echoes to voice users. These echo suppressors prevent simultaneous transmission in both directions and must be reversed, which occurs automatically when transmission ceases. The reversal requires about .15 to .20 seconds, so modems are usually designed to provide a fixed delay of about .200 seconds. Therefore, the delay between the end of a message block and the beginning of a reply is the sum of the transmission delay and .200 seconds. Since the mean delay of long distance calls (above 725 miles) is .015 seconds, this report uses .215 seconds for this delay.

For modems with bit rates above 2400, it is usually desirable to use an adaptive equalizer to reduce the effects of delay and amplitude distortion on the error rate. The adaptive equalizer on the modem model tested for 3600 and 4800 BPS required several seconds to recover after each reversal of the telephone line. For this reason the manufacturer provided a low speed reverse channel using a narrow portion of the telephone channel's bandwidth to permit transmission at 150 BPS. While it takes longer for the reply to be sent at 150 BPS, there is a time saving in not having to reverse the echo suppressors. Therefore, the total delay in this case is the transmission delay of .015 seconds.

Since some modems in the over 2400 BPS class are now being built with digital adaptive equalizers that require only .05 seconds recovery after a reversal of the direction of transmission, this report also considers this case. The time delay between the end of a message block and the beginning of a reply is assumed to be the sum of the transmission delay (.015 seconds), the reversal of the echo suppressor (.200 seconds), and the retraining of the digital adaptive equalizer (.05 seconds), for a total of .265 seconds.

The modems used for the survey have signaling rates that are widely used. ANSI Standard X3.1-1969[7/] lists the standard synchronous serial signaling rates as 600 times N bits per second, where N may be any positive integer from 1 through 16. The preferred standard signaling rates for the 1200 to 4800 BPS range are 1200, 2400 and 4800 BPS, while 2000 BPS is listed as an interim standard.

6. TRIB EQUATION

The calculation of TRIB involves the use of several terms, a few of which are sufficiently minor in their effect as to permit their being ignored in the TRIB equation without significantly affecting the value of TRIB. The equation used for the calculation of TRIB must include these terms: the block length in bits, the number of control characters per message block, the number of characters in the reply, the delay from the end of a message block to the beginning of the reply and the corresponding delay from the end of the reply to the beginning of the next message block, the bit rate for the message block, the bit rate for the reply (not always the same as for the message block), the number of bits per character (which is 8 for the synchronous modems and 10 for the asynchronous modems), and the ratio of the number of transmitted blocks to the number of accepted blocks. The last term accounts for all retransmissions, including those due to errors in the retransmissions.

As mentioned in the discussion of the control procedure, the effect of the heading is insignificant, so it is not included in the TRIB equation. There is a possibility of the reply being in error as well as errors in the recovery from a reply error. Fortunately, the reply has very few bits relative to the several hundred to many thousands of bits of the message blocks, so it is reasonable to assume no errors for the replies. Also, the remote possibility that the parity detection circuitry does not detect an error due to the particular bit pattern is insignificant so far as the calculation of TRIB is concerned.

The calculation of the ratio of transmitted blocks to accepted blocks implies a knowledge of the probability of a block being in error. The bit error rates that are obtained by dividing the total number of error bits by the total number of bits sent are not a realistic measure of the probability of a block being in error, as bit errors on the dial telephone network (and their private line counterparts) tend to be clustered into short bursts. The reason for this is that most errors are not the result of random (Gaussian) noise, but rather the result of various transient phenomena that affect several adjacent bits. The largest single cause of bit errors in data modems in the 1200 to 4800 BPS range is impulse noise. This noise is thought to be the result of switching in the telephone network and is usually characterized by several close together noise spikes each of several milliseconds duration. Since the amplitude of the noise spike may be high relative to the signal levels, the probability of error for each of the bits occurring at this time is quite high and several may be in error for each impulse spike. Rapid phase changes, sudden gain changes, line dropouts, and other dial telephone network phenomena of a transient nature tend to have a similar effect.

Since a block is rejected regardless of whether it has one bit in error or a hundred, this clustering of bit errors produces a pessimistic TRIB if it is used in the calculations; therefore, it is desirable to use an error rate that takes this burst effect into account. In the 1969-70 Connection Survey, the term "burst error rate" is used. It is defined in that particular study as "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." Burst error rates in the survey correlate closely with observed block error rates for all but the very longest block lengths. In this report, the probability of a bit being in error is taken from the burst error rate data in the survey. (See pages 1361 through 1365 of reference 5.)

The burst error rate, P, is related to the probability of the message block being without error by the expression"(1-P) to the Nth power." For computer calculation, this is usually solved by using the equality $X^Y = e^{Y \cdot \ln X}$. Unfortunately, the results are not sufficiently precise at the larger values of N and P.

For most values of N, the approximate equality (1-PN) = (1-P) to the N power may be used, but TRIB becomes pessimistic for the higher values of N.

The approach used for this report is a five-term binomial expansion. At very long block lengths and high values of P this expression also fails, but this is easily detected due to the drastic reversal in the direction of the curve.

TRIB Equation

TRIB (Transfer Rate of Information Bits) is defined by the equation:

$$\text{TRIB} = \frac{\text{Information bits per block}}{(\text{Time per block})\left(\dfrac{\text{No. of transmitted blocks}}{\text{No. of accepted blocks}}\right)}$$

$$\text{Information bits per block} = \left(\frac{7}{F}\right)\left(N - (8)(CC)\right)$$

Where 7 = number of information bits per character
F = number of bits per character including parity and start/stop bits (asynchronous only)
N = block length in bits
CC = number of control characters per message block

Time per block is the summation of the time for transmitting the message block plus the time for transmitting the reply plus twice the time between transmissions in opposite directions:

$$\text{Time per block} = \frac{N}{BP} + \frac{(F)(RY)}{BS} + (2)(D)$$

Where RY = number of characters per reply
BP = bit rate for message block
BS = bit rate for reply (not always = BP)
D = transmission delay + echo suppressor reversal delay + retraining digital adaptive equalizer (if used)

$$\frac{\text{No of transmitted blocks}}{\text{No. of accepted blocks}} = (1-E) + 2\cdot E\cdot(1-E) + 3\cdot E^2\cdot(1-E) + 4\cdot E^3\cdot(1-E) + \ldots$$

where E = probability of block being in error

$$= 1 - E + 2E - 2E^2 + 3E^2 - 3E^3 + 4E^3 - 4E^4 + \ldots$$

$$= 1 + E + E^2 + E^3 + \ldots$$

$$= \sum_{n=0}^{\infty} E^n \qquad \text{(Geometric Series)}$$

$$= \frac{1}{1 - E}$$

TRIB Equation (cont'd)

Combining these expressions in the original equation for TRIB:

$$\text{TRIB} = \frac{\left(\frac{7}{F}\right)\left(N - (8)(CC)\right)}{\left(\frac{N}{BP} + \frac{(F)(RY)}{BS} + (2)(D)\right)\left(\frac{1}{1 - E}\right)}$$

$$= \frac{(1 - E)\,\frac{7}{F}\left(N - (8)(CC)\right)}{\left(\frac{N}{BP} + \frac{(F)(RY)}{BS} + (2)(D)\right)}$$

The expression (1-E) is the only term that is not easily determined in the above equation. It is found from the equality:

$(1-E) = (1-P)^N$ where P is the probability of a bit being in error (P burst error rate)

The expression $(1-P)^N$ is evaluated using the binomial expansion.

The binomial expansion of $(1 + X)^N$ is:

$$(1 + X)^N = \frac{N!}{M!\,(N - M)!}\,X^M$$

therefore,

$$(1-E) = \frac{N!}{M!\,(N-M)!}\,(-P)^M$$

$$= 1 - N\cdot P + \frac{N(N-1)}{2}\,P^2 - \frac{N(N-1)(N-2)}{2\cdot 3}\,P^3 + \frac{N\,(N-1)(N-2)(N-3)}{2\cdot 3\cdot 4}\,P^4 + \ldots$$

Since it is unnecessary to evaluate all of the terms in the series, it is truncated to the first 5 terms and factored:

$$(1-E) = 1 + N\cdot P\left(-1 + \left(\frac{N-1}{2}\,P\right)\left(1 + \left(\frac{N-2}{3}\,P\right)\left(-1 + \frac{N-3}{4}\,P\right)\right)\right)$$

7. TRIB GRAPHS

The TRIB equation was used with FORTRAN programs to generate a series of graphs showing the variation of TRIB with the various parameters. Except where they are shown as variables in the graphs, the following values are used for each of the parameters: 10 bits per character for the 1200 BPS asynchronous modem and 8 bits per character for the synchronous modems; 3 control characters and 1 reply character for the asynchronous modem, and 7 control characters and 5 reply characters for the synchronous modems; a delay from the end of transmission in one direction to the beginning of transmission in the other direction of .215 seconds for the 1200 and 2000 BPS modems, .015 seconds for the 3600 and 4800 BPS modems when used with the secondary channel, and .265 seconds for the 3600 and 4800 BPS modems when used without the secondary channel (assumes a digital adaptive equalizer); a 150 BPS rate for the secondary channel (when used); and the burst error rate for the 50th percentile of the calls. The burst error rate data is from the burst error rate graphs in the 1969-70 Connection Survey. (These graphs show a rapidly increasing burst error rate for calls above the 90th percentile, while the variation in the error rate is much less marked for calls below about the 90th percentile.) The accuracy of the TRIB values for extremely long block lengths of 50,000 and 100,000 bits may be less than that for block lengths of 10,000 bits or less, as error burst rate to block error rate relationship in the survey is only shown for block lengths through 10,000 bits.

Burst Error Rate Data from the 1969-70 Connection Survey

Modem Bit Rate in BPS	Burst Error Rates for Percentiles of Toll Calls on the Dial Telephone Network (Best call = 0th Percentile)		
	50th Percentile	90th Percentile	95th Percentile
1200	6.0×10^{-7}	7.0×10^{-6}	2.0×10^{-5}
2000	4.5×10^{-7}	4.5×10^{-6}	1.0×10^{-5}
3600	1.0×10^{-6}	1.0×10^{-5}	3.2×10^{-5}
4800	1.7×10^{-6}	3.0×10^{-5}	1.0×10^{-4}

Figures 1 through 6 show TRIB versus block length for each of the four modem types. There are two graphs each for the 3600 and 4800 BPS modems, so that TRIB can be shown both with and without the secondary channel. On each graph curves are shown for the 50th, 90th and 95th percentiles of the telephone calls, as ranked by their burst error rates. (Users may prefer to hang up and dial again for calls in the top 5 or 10 percentiles.)

The optimum block length varies with the burst error rates and with modem bit rate. At very short block lengths TRIB is quite low due to the fixed line turnaround delays and to the fixed time required for transmitting the replies. At very long block lengths TRIB drops due to the increasing probability of one or more bits in the block being in error and the message block being retransmitted. The optimum block length choice would certainly depend upon whether it is feasible to hang up and dial again for calls with high error rates.

TRIB, as a percentage of the bit rate of the synchronous modems, is limited to 87.5 percent by the X3.28 requirement of a parity bit for each character, while with asynchronous modems this drops to 70 percent due to the start and stop bits. (A control procedure using a polynomial code would not require a parity bit for each character and would have a substantially higher TRIB.) At the 50th percentile and a block length of 10,000 bits; the 1200 BPS modem has an efficiency of 66 percent, the 2000 BPS modem an efficiency of 79 percent, the 3600 BPS modem has efficiencies of 78 and 72 percent with and without the secondary channel, and the 4800 BPS modem has efficiencies of 75 and 68 percent with and without the secondary channel.

The graphs are discontinuous when the next computed value for TRIB is invalid due to the high values of N and P in the binomial expansion.

Figure 7 shows TRIB versus block length for the four modems on the same graph with the burst error rates of each modem at the 50th percentile and with the use of the secondary channel for the 3600 and 4800 BPS modems. Figure 8 shows the same curves for each modem, but with the burst error rates at the 90th percentile. The 4800 BPS modem offers a substantial performance improvement over the 3600 BPS modem at the 50th percentile, but at the 90th percentile offers a minimal improvement and a greatly increased sensitivity to block length.

Figures 9 through 14 show TRIB as a function of burst error rate for each of the modems, with separate curves for block lengths of 1,000, 10,000 and 100,000 bits. Since error rates tend to be in the range of 10^{-7} to 10^{-4}, the ends of the graphs are shown only to illustrate the effect of the error rate on TRIB. When data transmission must take place on telephone lines with high error rates, the use of short block lengths is desirable and in extreme cases virtually essential.

Figures 15 through 18 show TRIB as a function of block length for burst error rates at the 50th percentile and with curves for different telephone line delays. With the 1200 and 2000 BPS modems, the delays are: for calls only to nearby locations (no echo suppressor); for use with any dial call, but showing a lower echo suppressor delay for illustration ; any dial call with the usual echo suppressor delay setting for the modem; and for calls via satellite with an estimated .300 seconds transmission delay for the satellite link. With the 3600 and 4800 BPS modems, the delays are: for calls to nearby locations; calls to locations several hundred miles away; and for calls via satellite. (All of these delays are doubled in the TRIB equation for the two line reversals needed for each block.) As might be expected, the effect of variations in the delay is greatest with the shorter block lengths and almost insignificant with very long blocks. At moderate block lengths, the effect is quite significant.

This initial report on a specialized aspect of data communications performance is to be followed by more extensive reports in collaboration with the Institute for Basic Standards. These reports will cover a much broader area of data communications and will involve both the measurement of parameters influencing digital data transmission and the optimization of systems performance.

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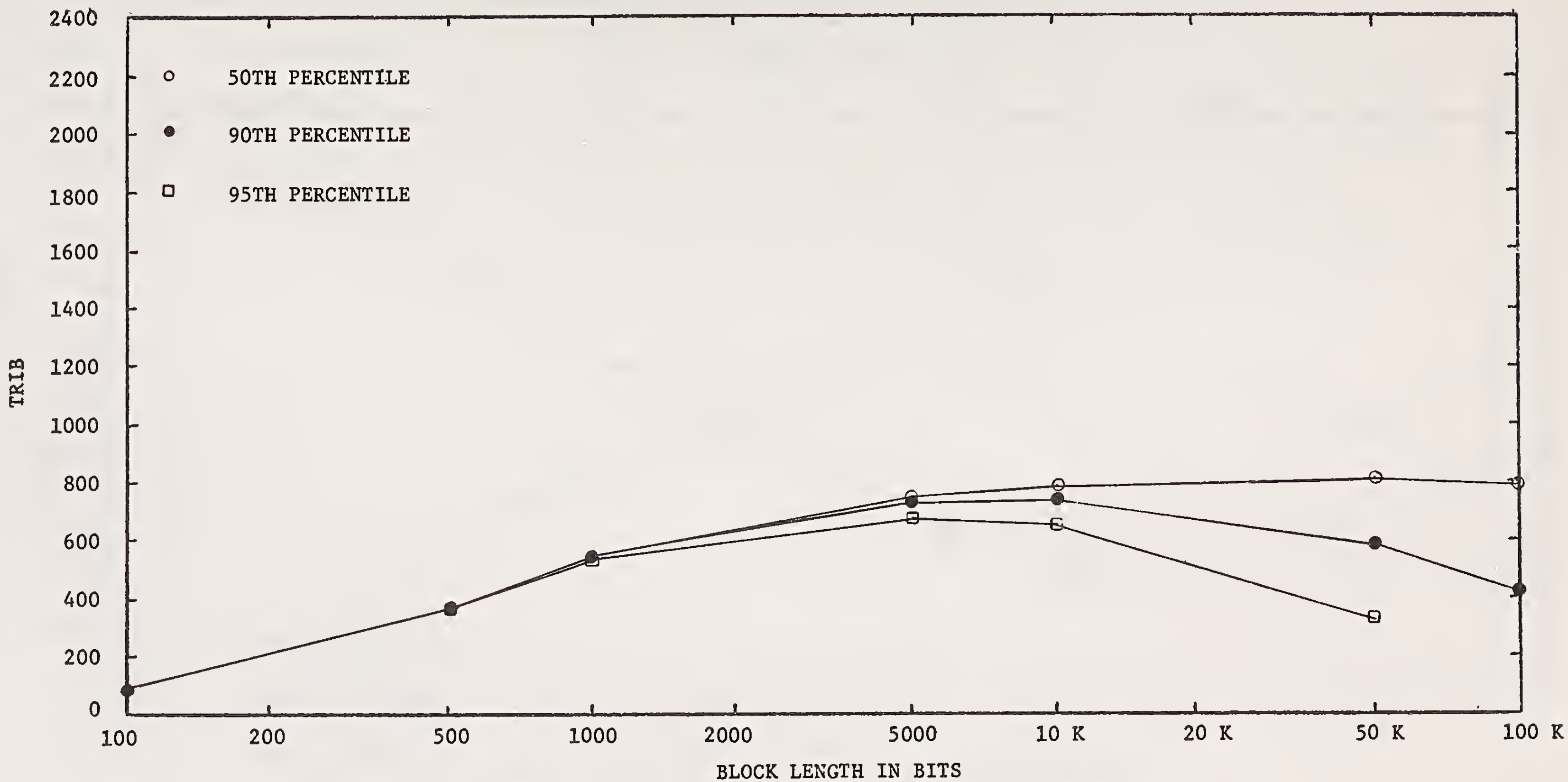
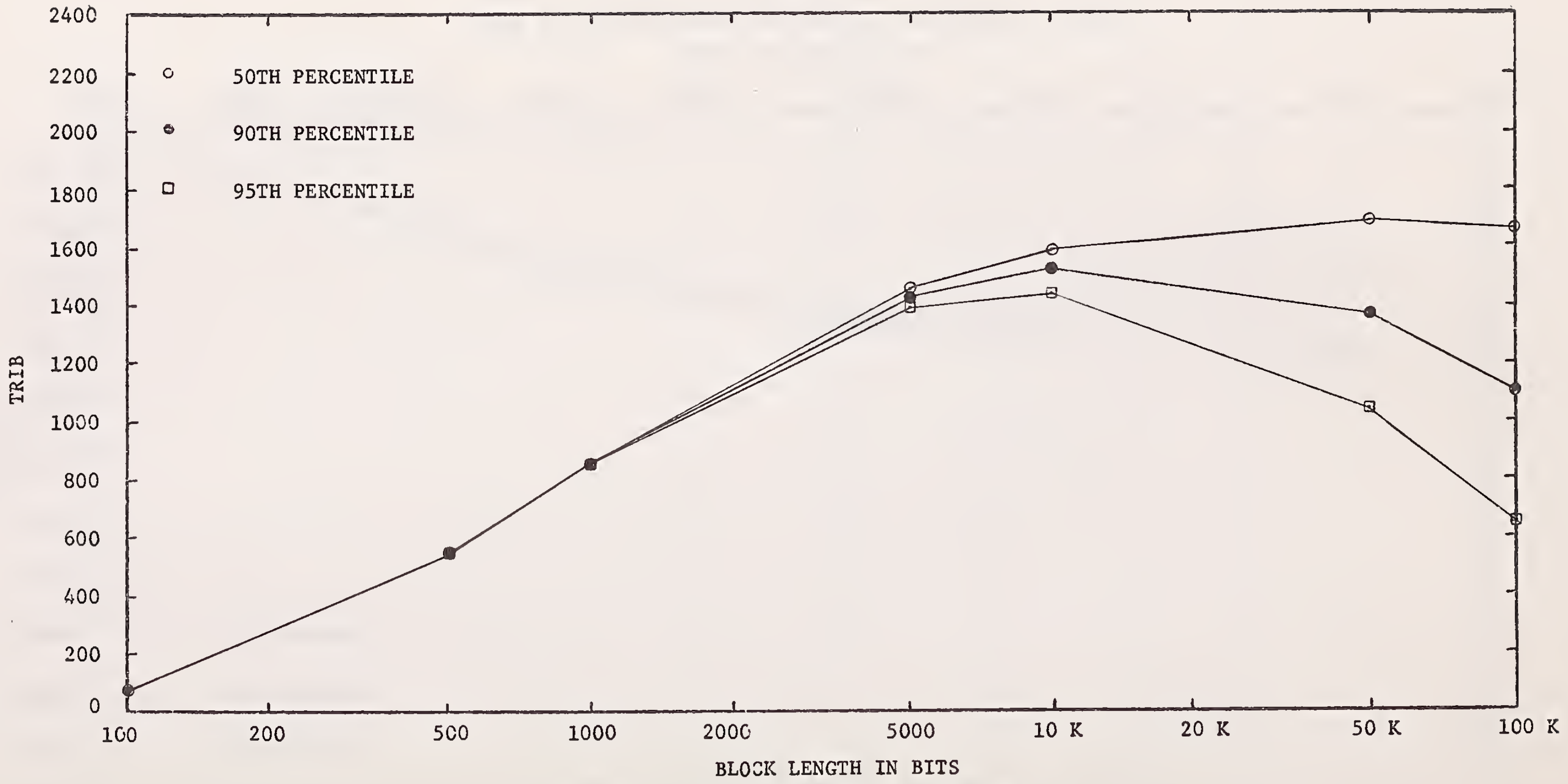
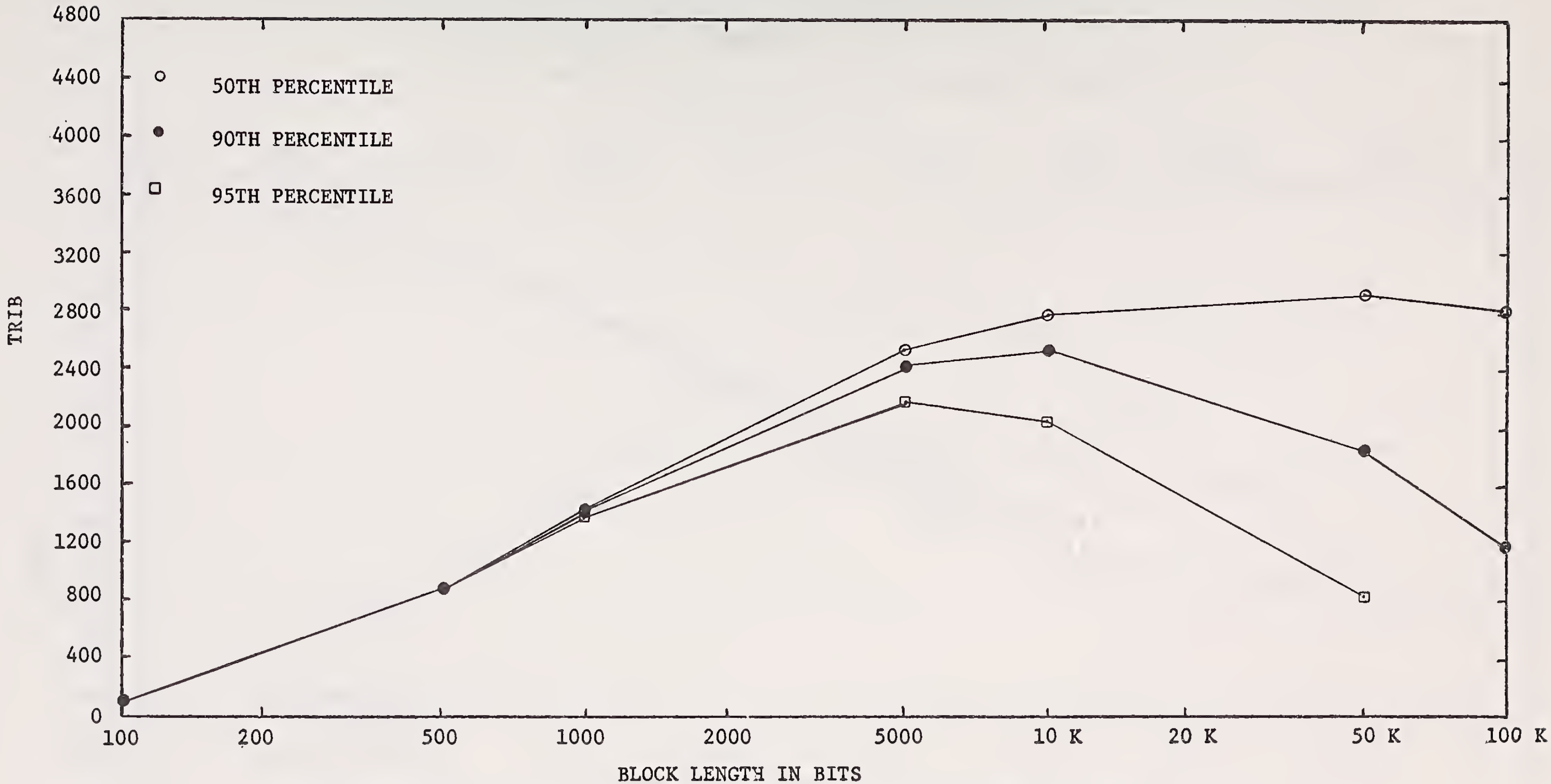


TRIB vs. Block Length for 1200 BPS Asynchronous Modem

Figure 1

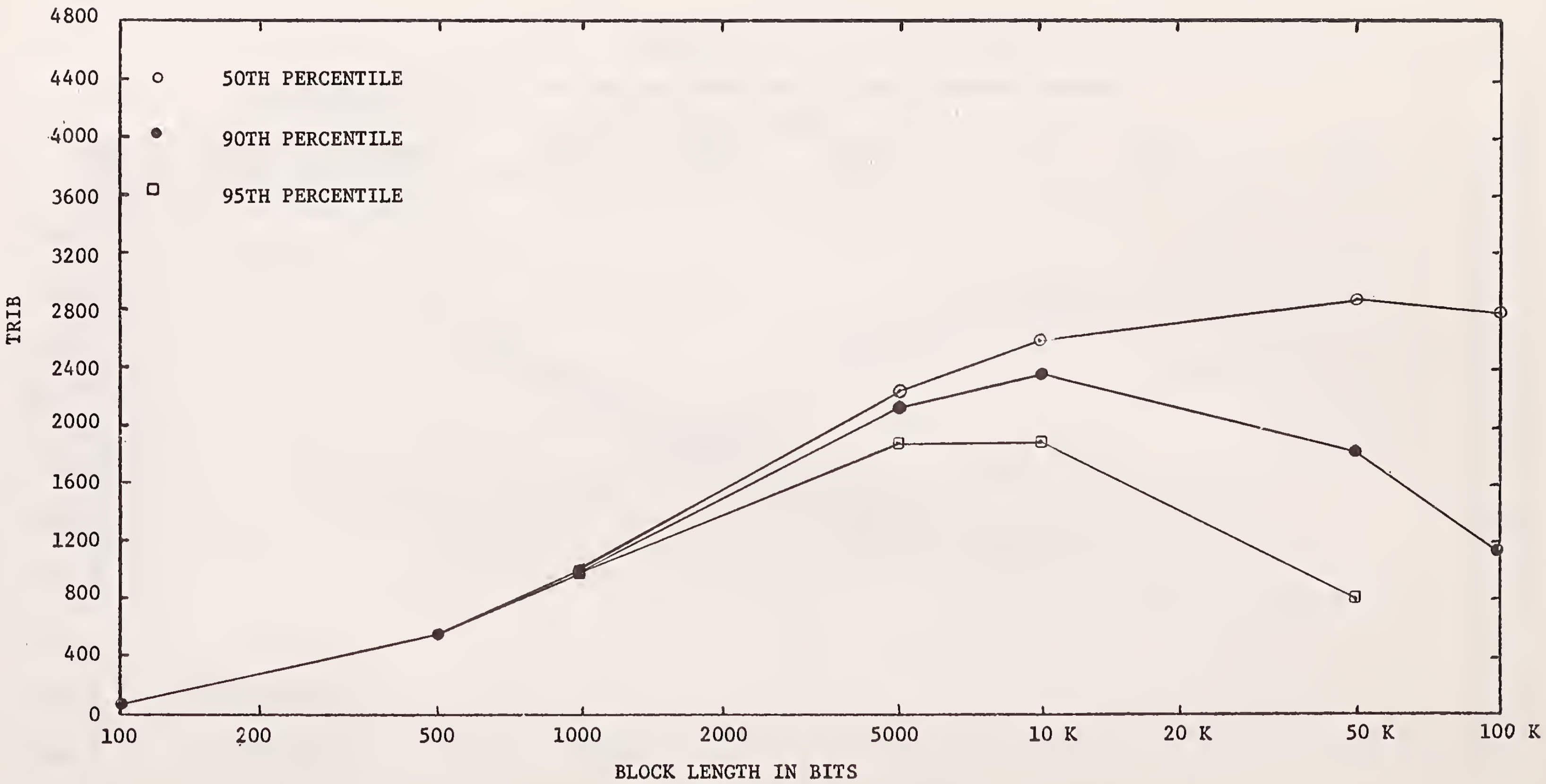


TRIB vs. Block Length for 2000 BPS Modem
Figure 2



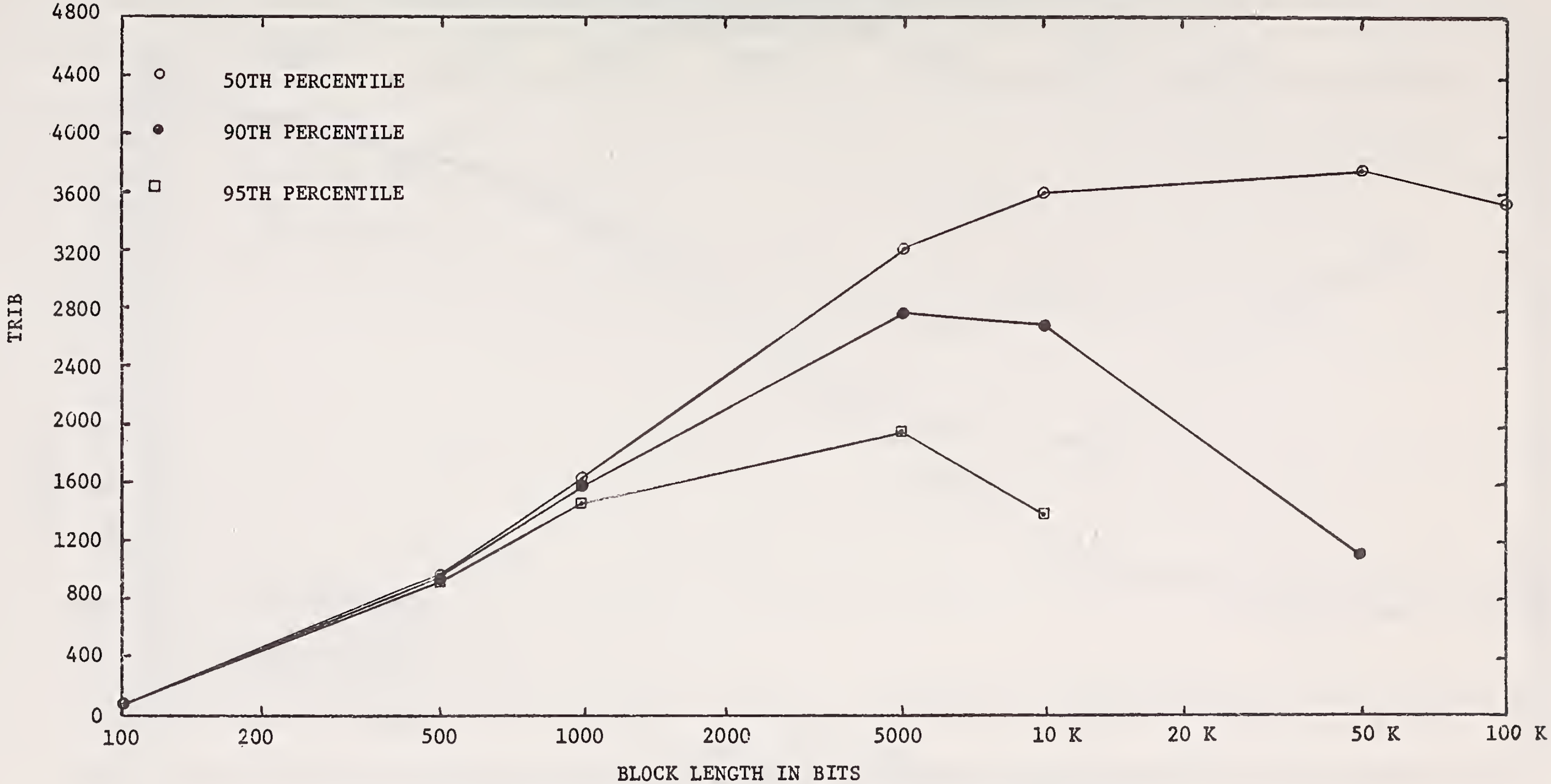
TRIB vs. Block Length for 3600 BPS Modem with 150 BPS Secondary Channel

Figure 3



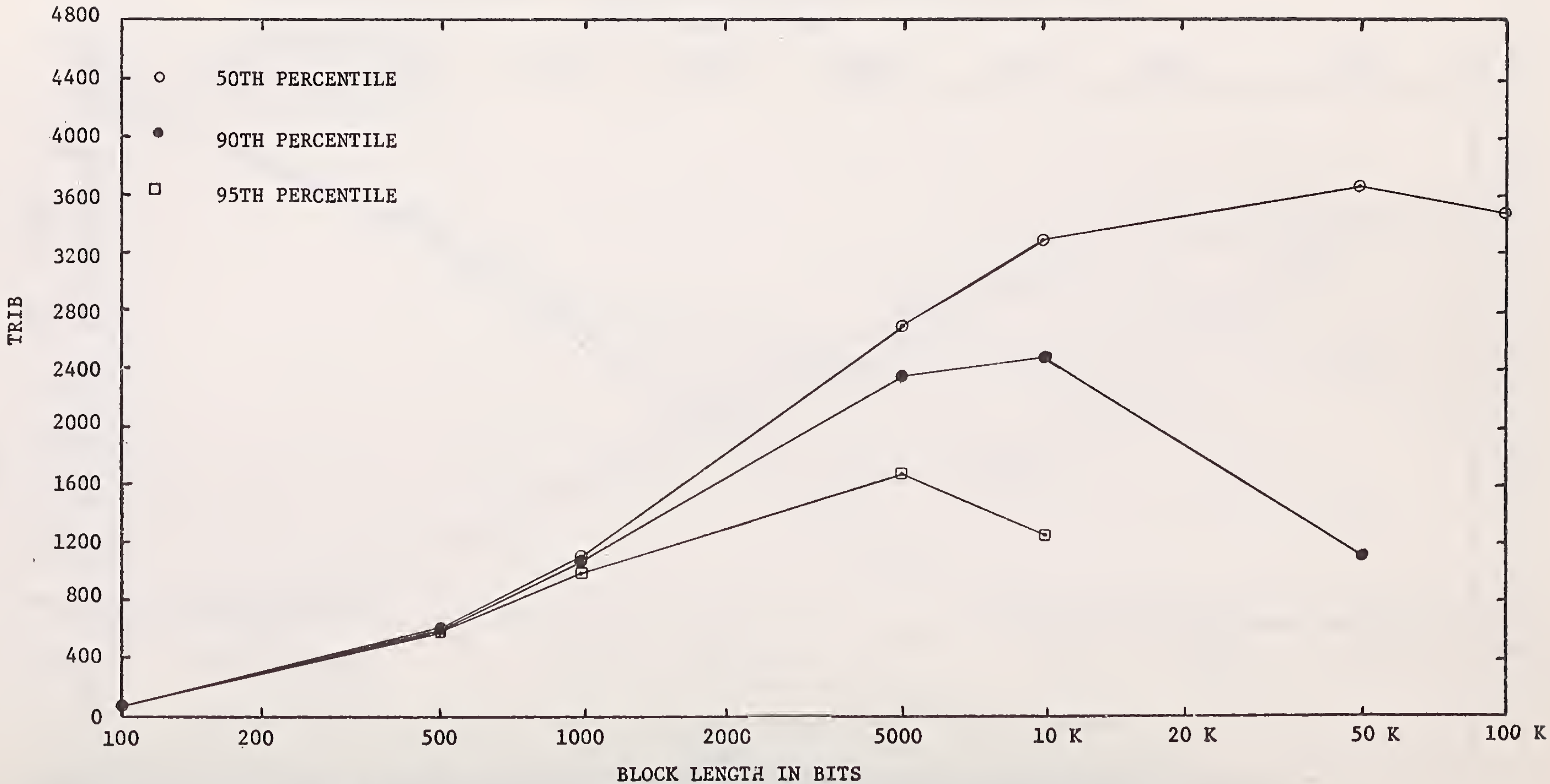
TRIB vs. Block Length for 3600 BPS Modem without Secondary Channel

Figure 4



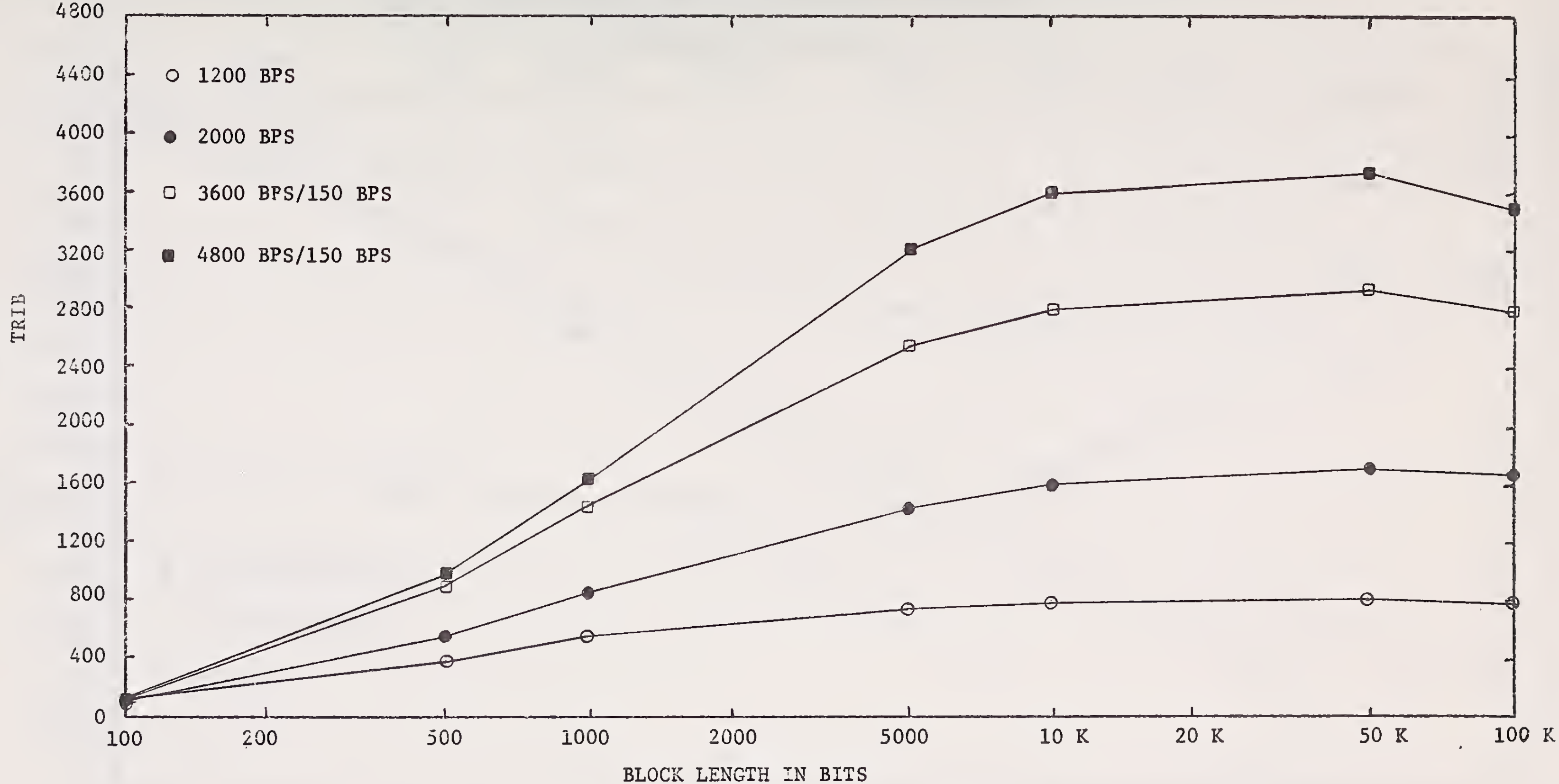
TRIB vs. Block Length for 4800 BPS Modem with 150 BPS Secondary Channel

Figure 5



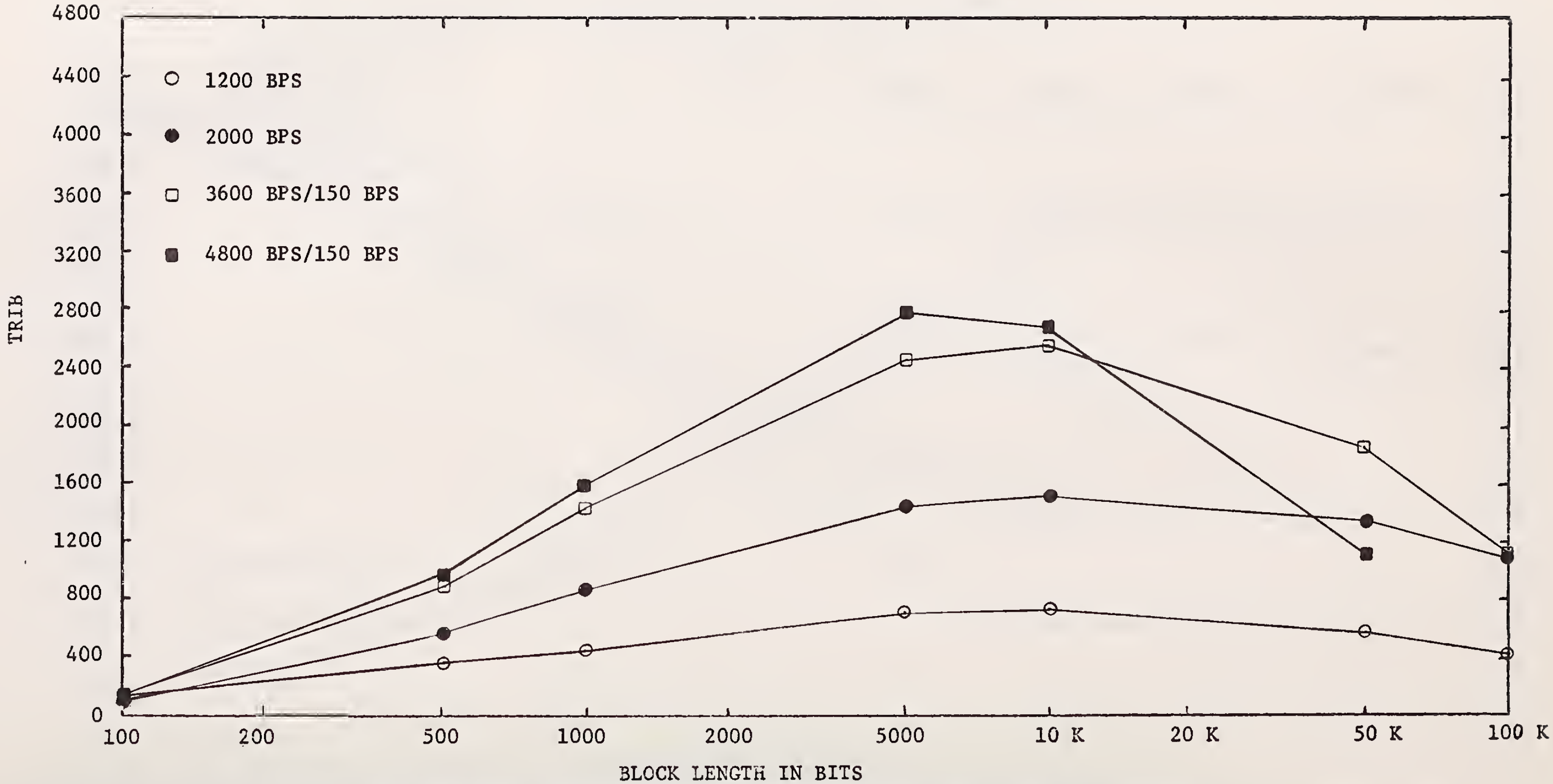
TRIB vs. Block Length for 4800 BPS Modem without Secondary Channel

Figure 6



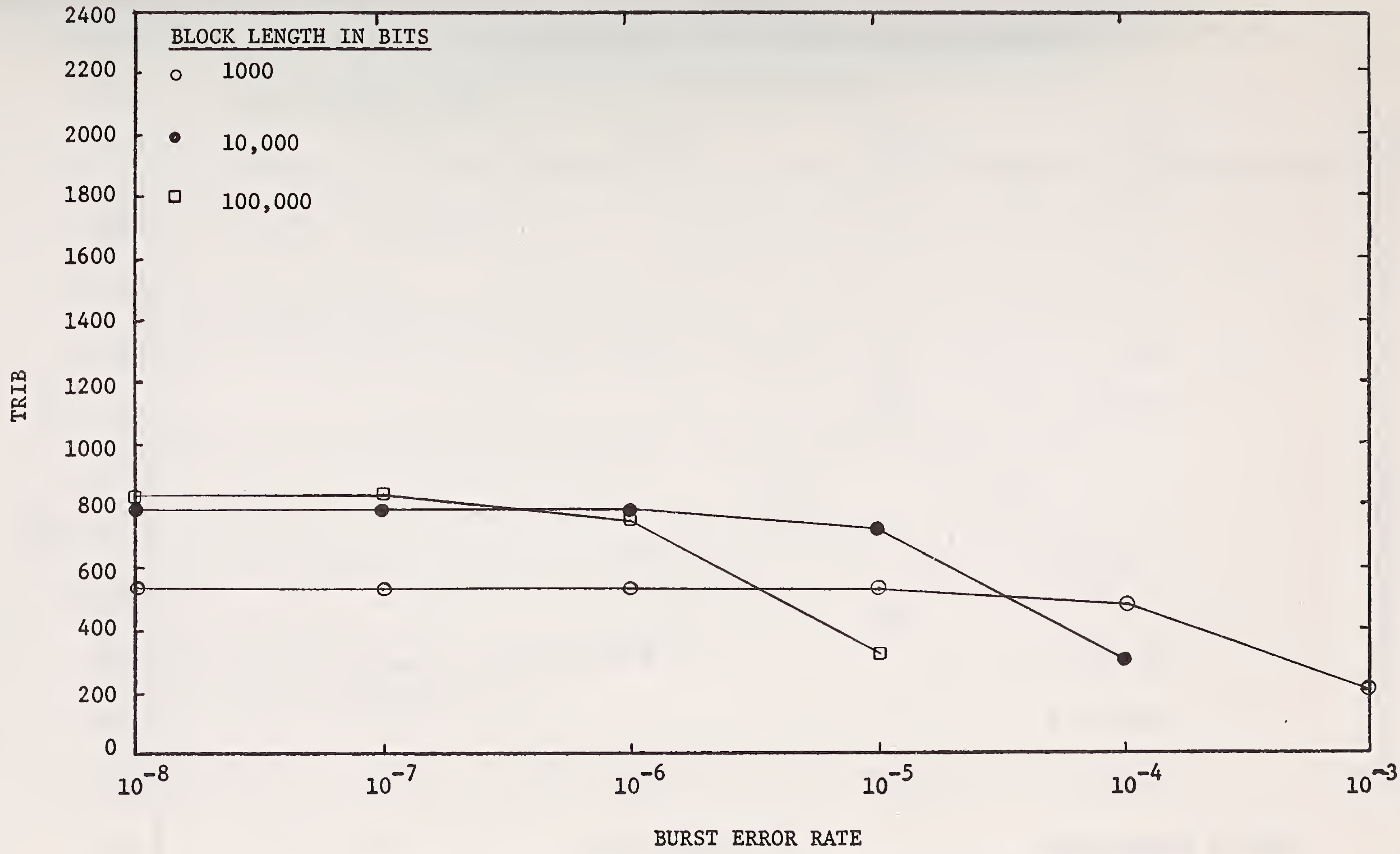
TRIB vs. Block Length for 50th Percentile of All Calls

Figure 7



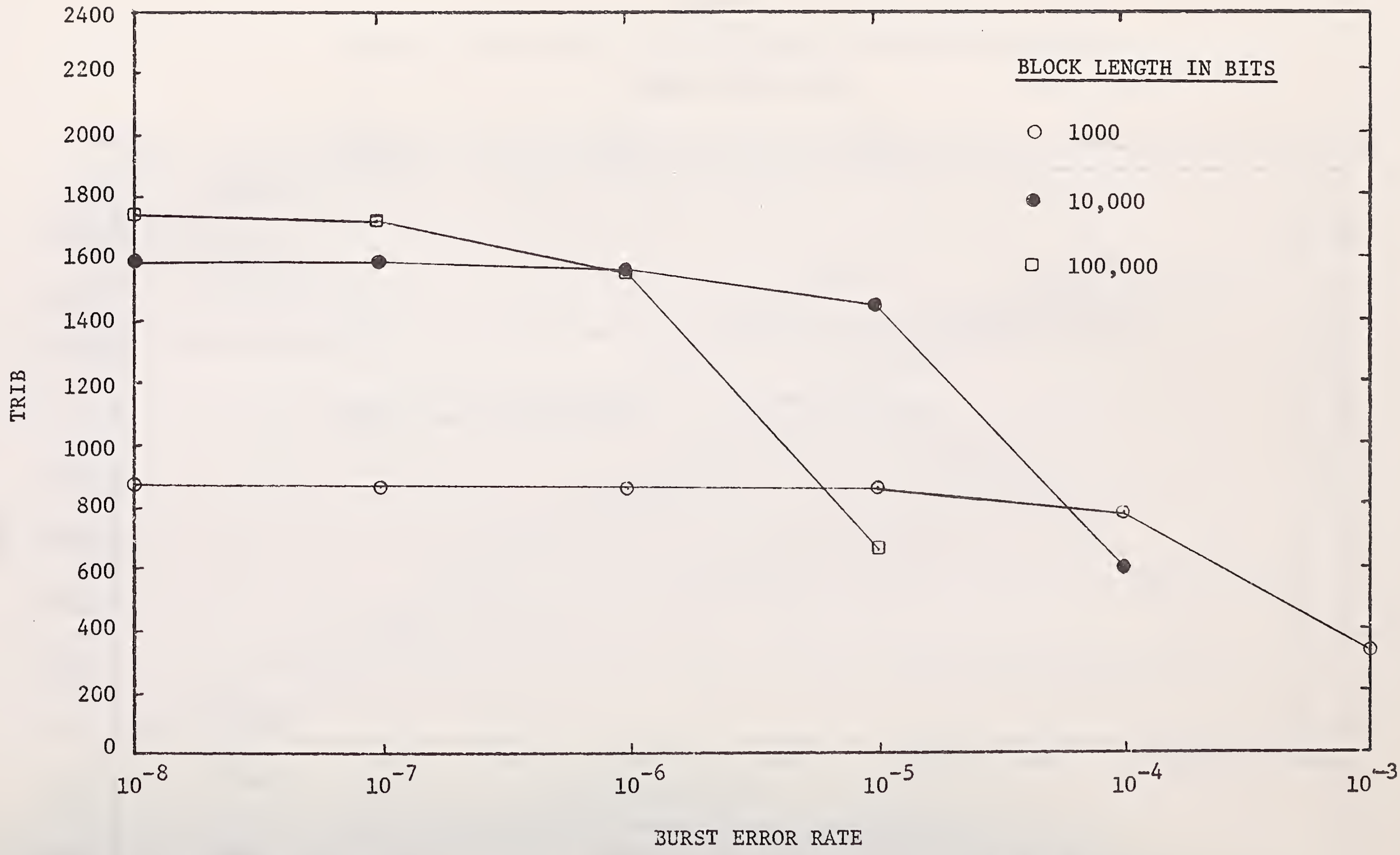
TRIB vs. Block Length for 90th Percentile of All Calls

Figure 8



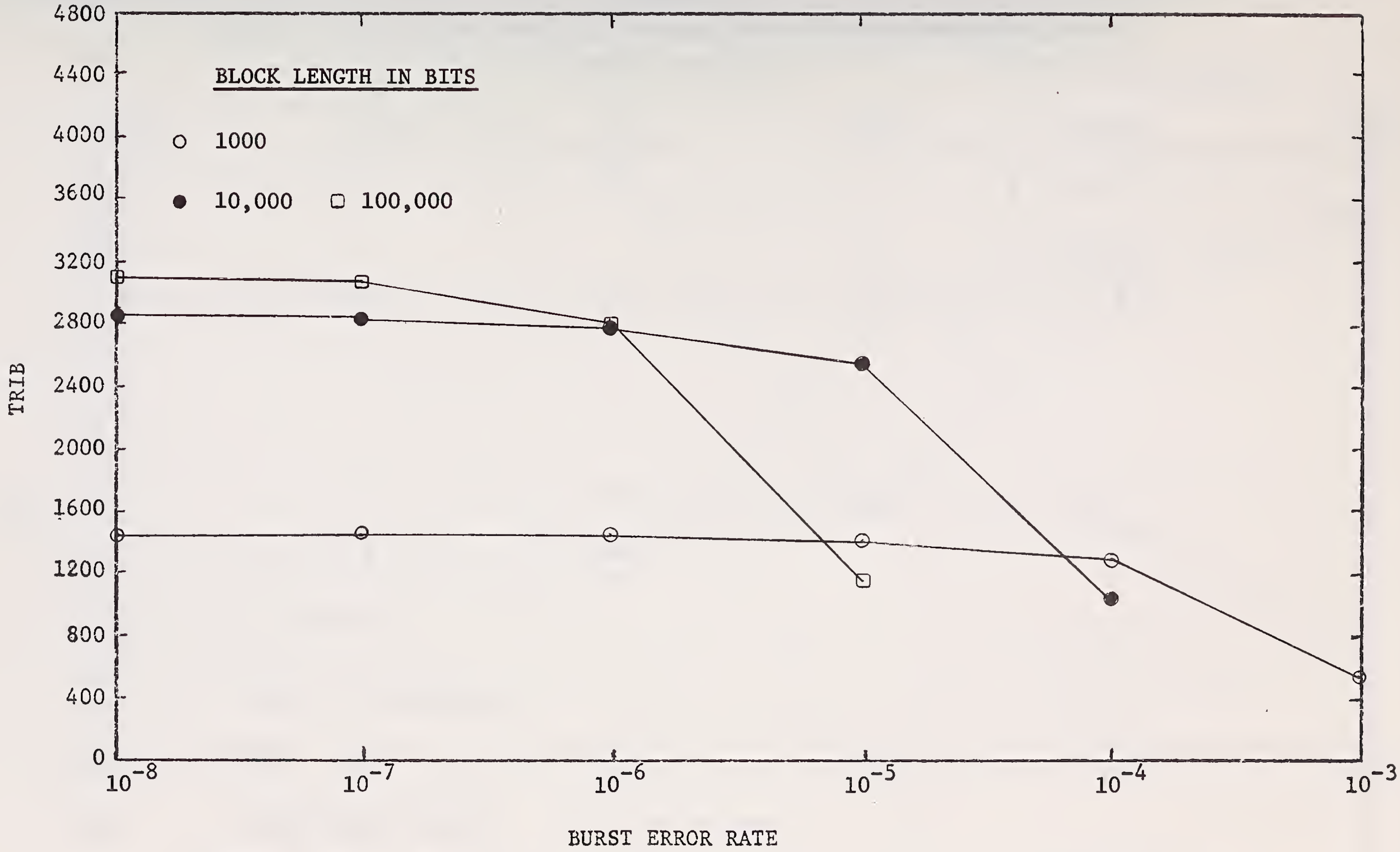
TRIB vs. Burst Error Rate for 1200 BPS Asynchronous Modem

Figure 9



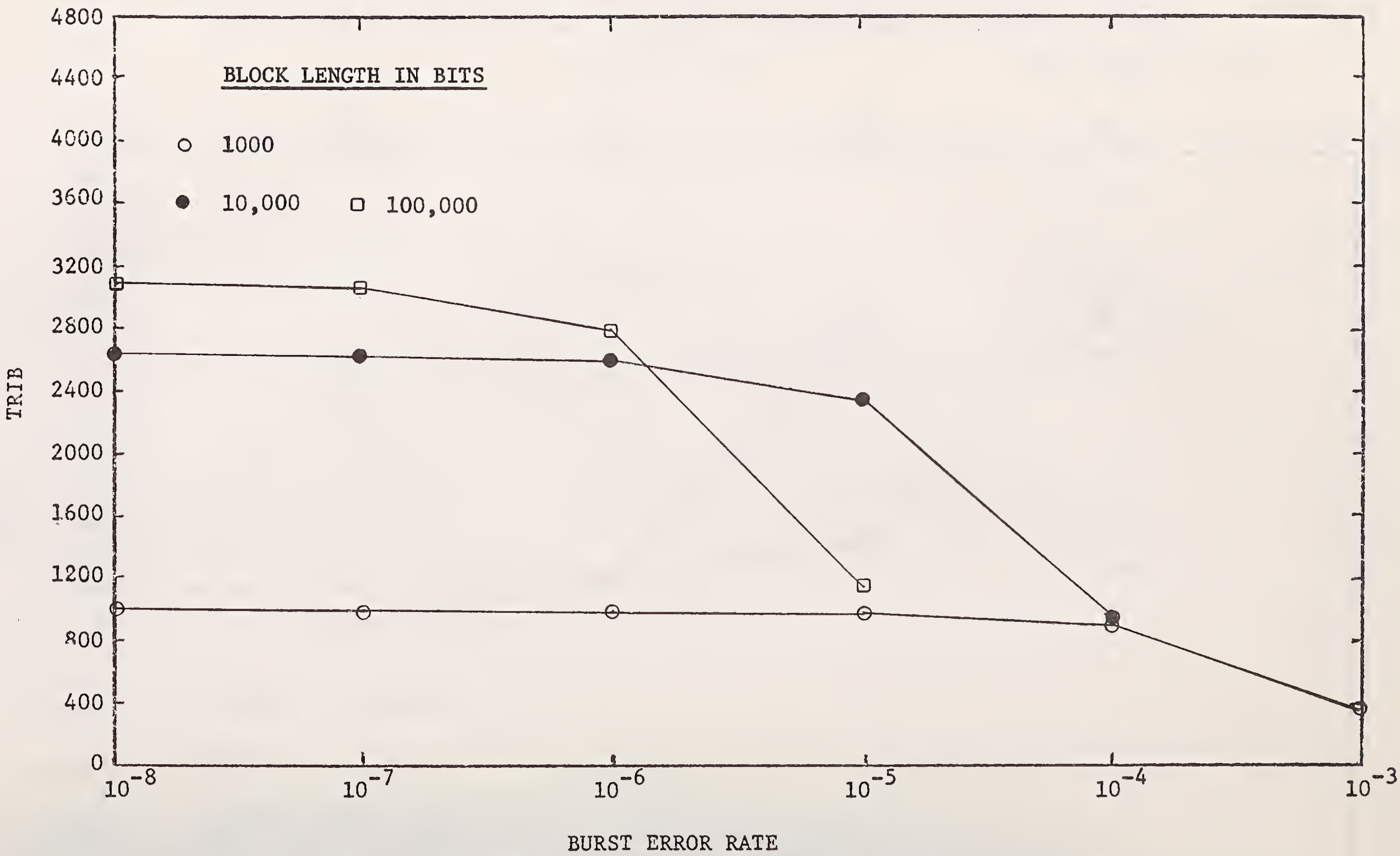
TRIB vs. Burst Error Rate for 2000 BPS Modem

Figure 10



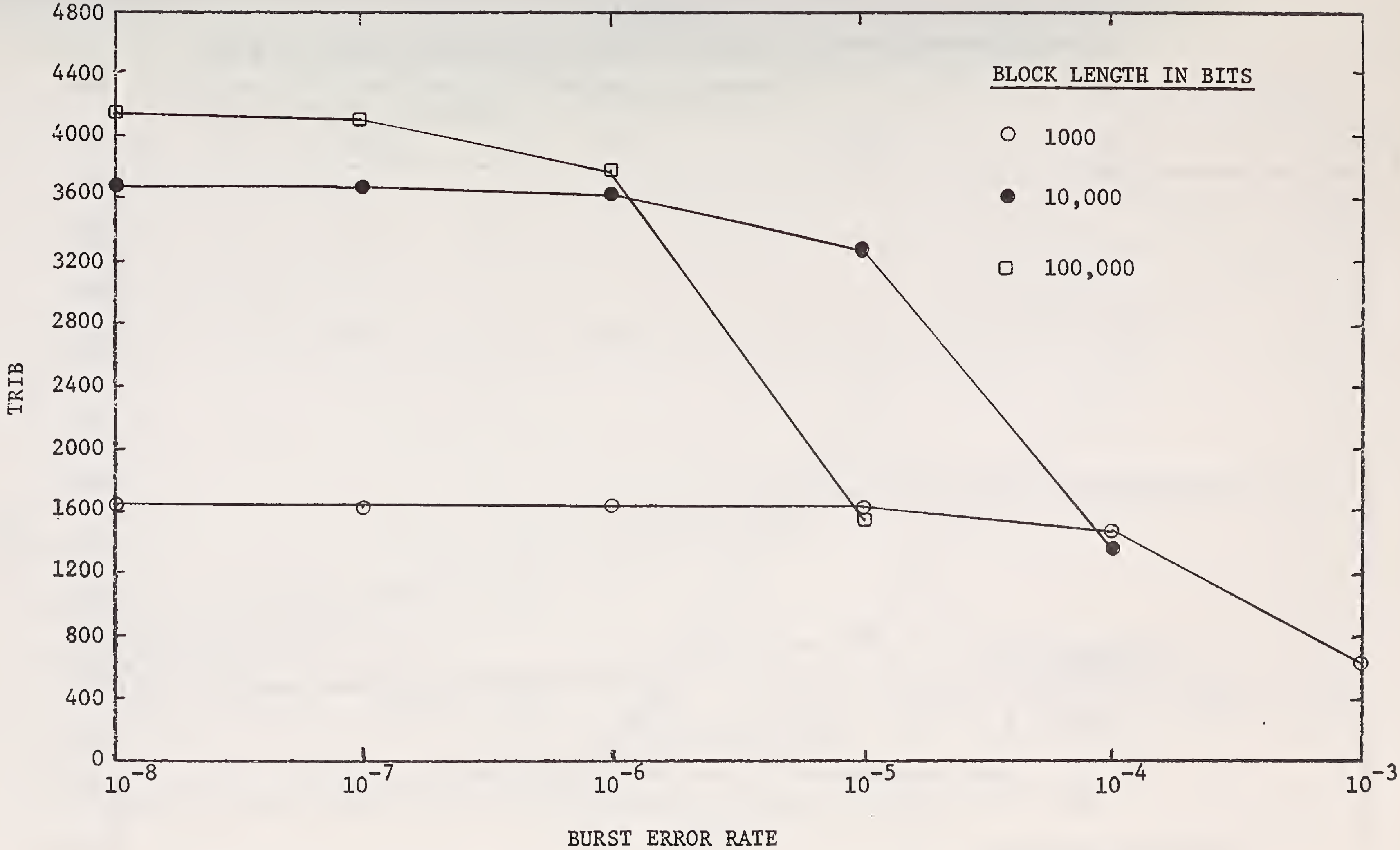
TRIB vs. Burst Error Rate for 3600 BPS Modem with 150 BPS Secondary Channel

Figure 11



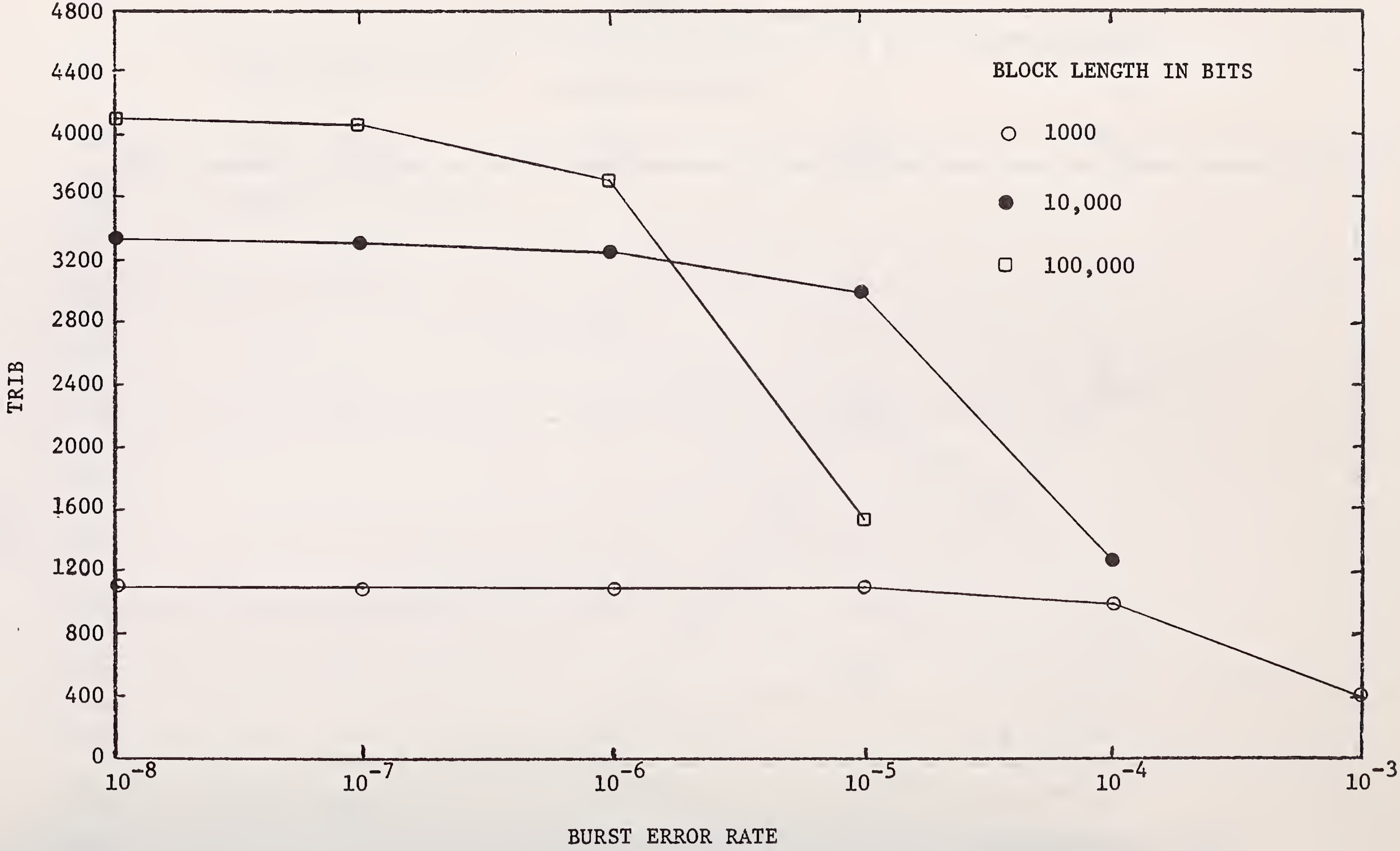
TRIB vs. Burst Error Rate for 3600 BPS Modem without Secondary Channel

Figure 12



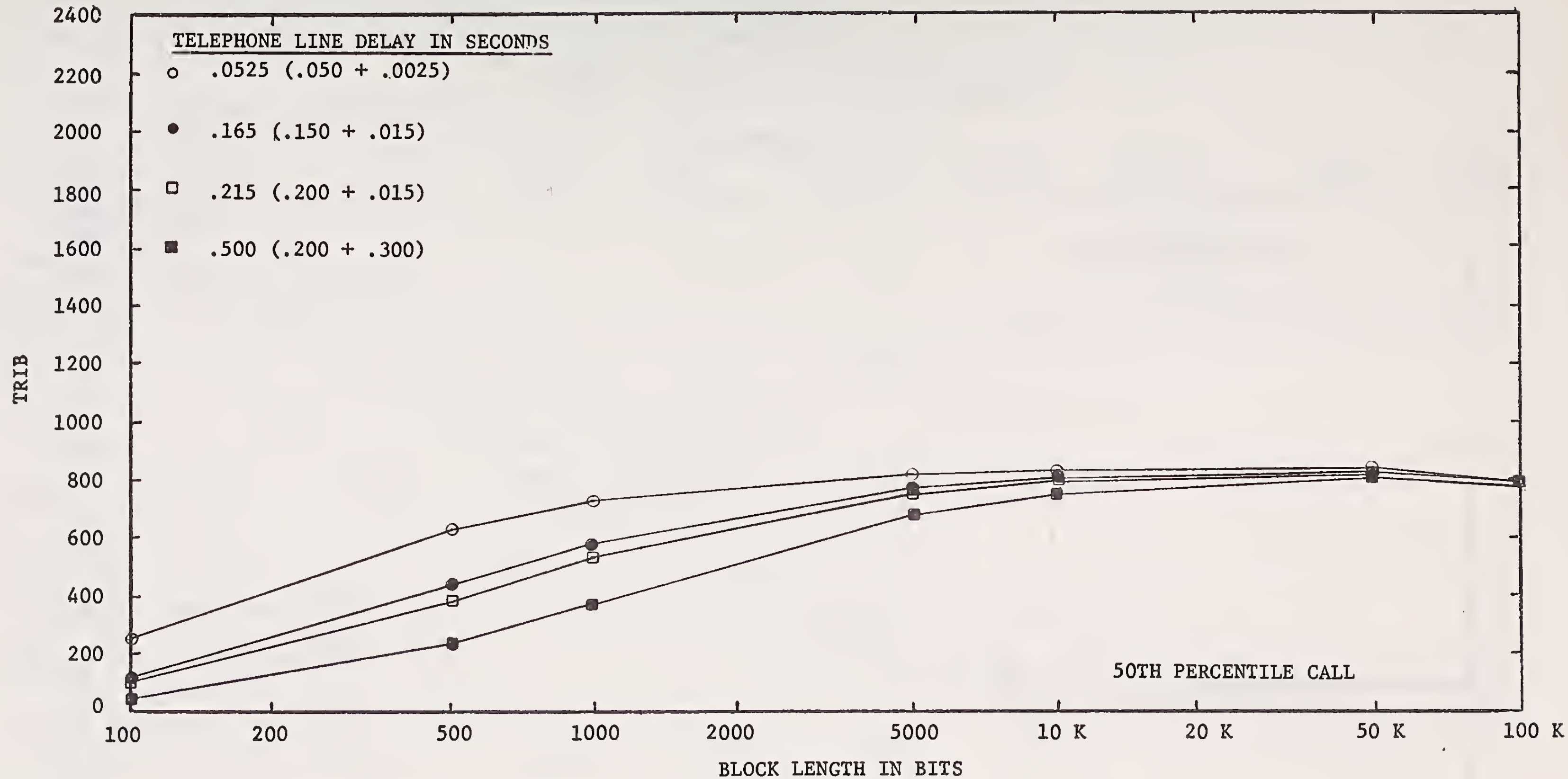
TRIB vs. Burst Error Rate for 4800 BPS Modem with 150 BPS Secondary Channel

Figure 13



TRIB vs. Burst Error Rate for 4800 BPS Modem without Secondary Channel

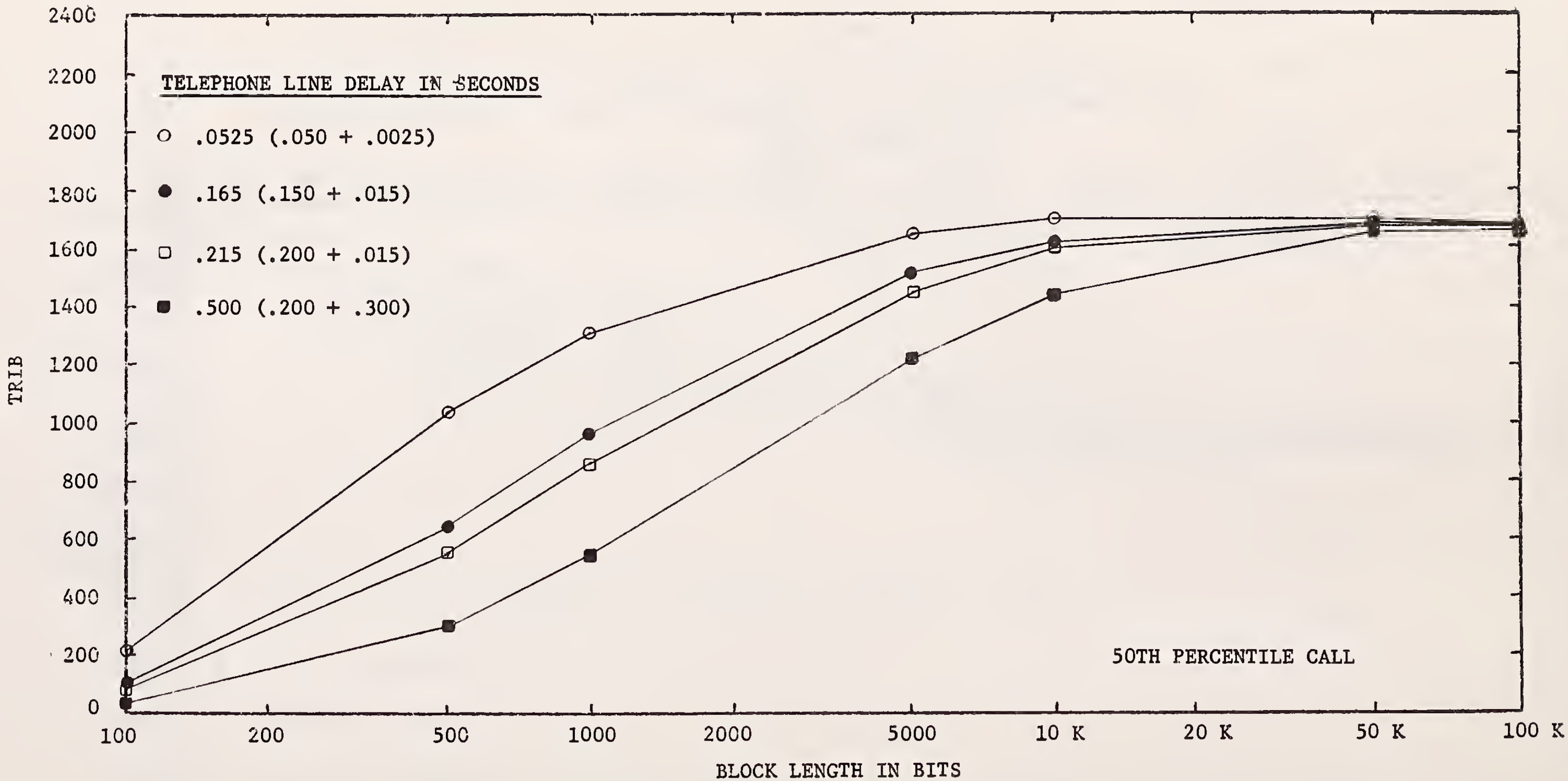
Figure 14



TRIB vs. Block Length for 1200 BPS Asynchronous Modem

Effect of Different Telephone Line Delays

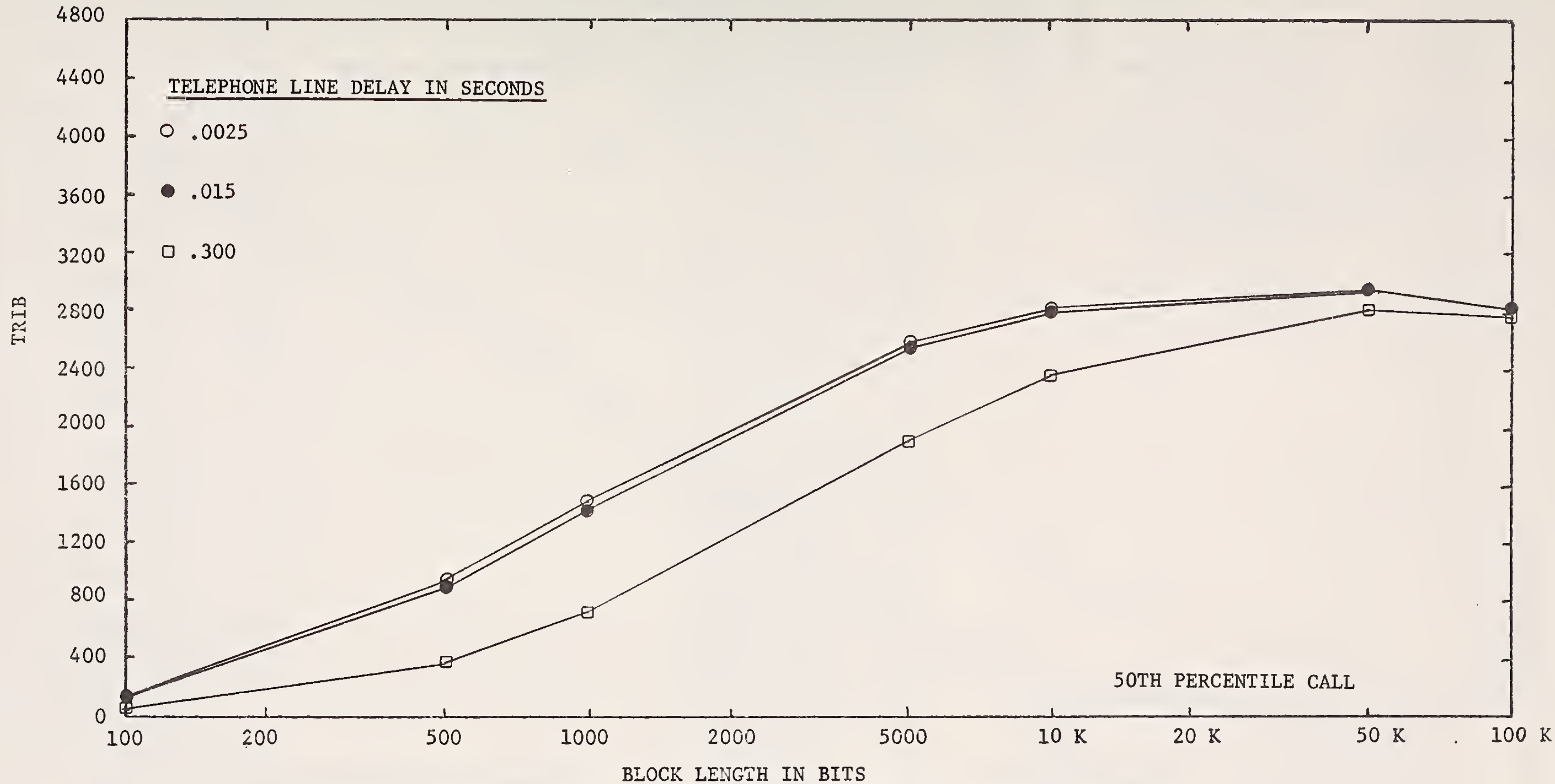
Figure 15



TRIB vs. Block Length for 2000 BPS Modem

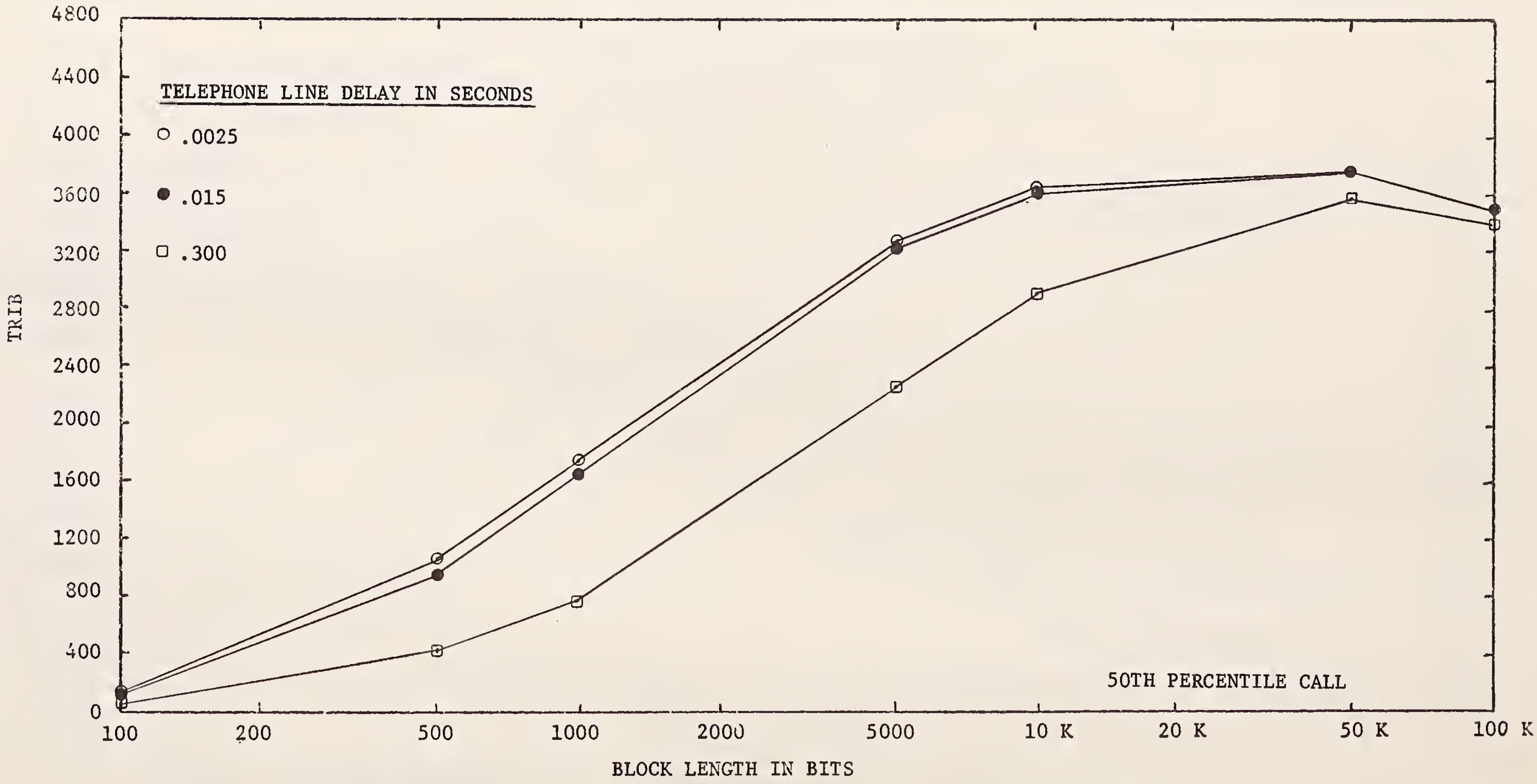
Effect of Different Telephone Line Delays

Figure 16



TRIB vs. Block Length for 3600 BPS Modem with 150 BPS Secondary Channel
Effect of Different Telephone Line Delays

Figure 17



TRIB vs. Block Length for 4800 BPS Modem with 150 BPS Secondary Channel
Effect of Different Telephone Line Delays
Figure 18

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16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

Throughput performance of high speed data terminals using the dial telephone network is calculated for signaling rate of 1200 to 4800 bits per second using the ANSI X3.28-1971 control procedures and measured in terms of the proposed ANSI strand TRIB described in X3S35/80. The performance calculations are shown graphically with TRIB as a function of block length, error rates of the telephone connection, signaling rate and telephone line delays. Error rates are based on a published survey involving several hundred telephone connections to geographically distributed parts of the United States.

17. KEY WORDS (Alphabetical order, separated by semicolons)
Data communications; modems; terminals; throughput; TRIB.

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