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BLOCK ERROR PATTERNS AND THROUGHPUT RATE ON THE DIGITAL HIGH-SPEED AUTOVON CHANNEL

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Voice telephone systems, such as AUTOVON, have been used for the transmission of high-speed digital data. In this paper, the performance of AUTOVON circuits in passing 4800 b/s and 9600 b/s digital data using the state-of-the-art Codex 9600 modem is presented. It is demonstrated that the channel provides stable values of block error rate over long periods of time. Additionally, it is demonstrated that the

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20. Abstract (continued)

maximum value of link throughput rate occurs at a block length of 9000 bits and that throughput rate is also reasonably constant as a function of time. Finally, a block error channel model is included for use in simulations where block retransmissions must be considered.

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INTRODUCTION

In recent years there has been, within both the civil and military environments, a trend toward the use of voice grade circuits (nominally 2400 Hz of usable bandwidth) for high-speed digital data transmission. This trend has developed because of the need to interconnect computers and computer-like devices on existing communications circuits at data rates sufficiently high for the achievement of operational computer efficiency. A natural outgrowth of efforts in this direction is the use of common-user voice grade circuits of the Defense Communication Agency's AUTOVON for digital data transmission at the state-of-the-art speeds up to 9600 b/s.

The Electronic Systems Division of the Air Force Systems Command is presently developing (in conjunction with the Strategic Air Command (SAC) and MITRE) a new continental U.S. record data communications system for SAC called the SAC Automated Total Information Network (SATIN IV). Since AUTOVON is the primary candidate for use as the backbone transmission facility for SATIN IV, a study was undertaken to determine the digital characteristics of AUTOVON. As a first step in this study, digital error patterns measured on AUTOVON circuits have been analyzed [1,2].

In this paper, as a follow on effort, consideration is given to how block errors, at the SATIN IV block length of 260 characters, are distributed. It is demonstrated that while both short and long runs of block errors can occur, the distribution of block errors is insensitive to time and there is little to be gained by abandoning a circuit exhibiting a high block error rate for a new circuit. This new circuit will most likely exhibit the same block error distribution. As an aid in channel simulation, the block error channel model is also presented. Finally, a discussion of throughput rate as a function of block length and time is presented. It is demonstrated that there is a maximum throughput rate occuring at 9000 bits at 4800 bits/sec. and at 3900 bits at 9600 bits/sec. This throughput rate is affected very little by transmission time. This fact reinforces the idea that it is pointless to trade in a high block error rate circuit on a new unknown circuit.

SECTION II

AUTOVON CHANNEL TESTS

AUTOVON

AUTOVON is basically a network of voice grade wireline circuits and microwave links crisscrossing the United States in a similar fashion to the commercial telephone system. The use of AUTOVON is limited to authorized agencies of the United States Government. The network contains switches (i.e., ESS and CROSS-BAR) of the same type as commercial communications. These switches provide the call routing and interconnection functions of AUTOVON. The network is made up of unconditioned Common Grade [3] Leased Lines. The performance of AUTOVON when used for digital data transmission is related to amplitude and phase distortion, channel noise, and phase jitter, and the manner in which the decision algorithm of the data transmission modem responds to these channel conditions. Thus, the true digital data channel is not AUTOVON alone, but rather AUTOVON in conjunction with the modem used. The modem utilized for the channel tests reported herein was a state-of-the-art Codex 9600 modem. This modem was employed because it was the only on-hand government-owned 9600 b/s telephone line data modem available at the test site during the test period.

The Codex 9600 modem is designed to transmit 4800, 7200, or 9600 b/s serial, synchronous digital data at a 2400 baud signaling rate over a dedicated type 3002, C2 conditioned, 4-wire telephone circuit. It is a full-duplex, double sideband, suppressed-carrier modem using a combination of amplitude- and phase-shift keying with transversal filter equalization. The transmitted signal occupies a 2500 Hz spectrum centered at 1706 Hz. Each baud contains information from a 4-bit sample of 9600 b/s, a 3-bit sample of 7200 b/s, or a 2-bit sample of 4800 b/s input data. Input data is scrambled before transmission to prevent the receiver from becoming sensitive to data patterns and to provide a uniform line-signal spectrum for the equalization process. Receiver-carrier and timing-recovery circuits use information contained in the transmitted data to eliminate the need for the transmission of pilot tones.

Test Procedure

The AUTOVON performance was measured by establishing a data transmission facility and transmitting data through the Codex 9600 modem. When the signal was received by the receive modem, decisions as to bit values were made, and the received bit sequence (suitably delayed to account for transmission delay) was added modulo 2 with no carry to the transmitted sequence. This summation (a bit-by-bit error pattern) was then recorded on computer compatible magnetic tape in a suitable format for later statistical analysis. Although dialing for call connections was to target switches, the trunks were randomly selected by the inherent nature of call dialing.

In all cases, data transmission originated at the Rome Air Development Center (RADC), Griffiss AFB, New York, and proceeded via C-3 conditioned access lines to the Tully, New York AUTOVON switch. From Tully, connections were made to the switches at Pottstown, PA; Arlington, VA; Rockdale, GA; and Santa Rosa, CA (in varying orders and combinations). The return connection was back to RADC via Tully. Of these switches, only Arlington, VA, was an ESS. Testing was conducted at all times of the day and test runs were, for the most part, 30 minutes or 1 hour in duration with redialing between runs.

Data Sample Size

The amount of data collected is summarized in Table 1. Over 3 billion bits were collected at 4800 b/s and almost 4 billion bits were collected at 9600 b/s. The first interesting point to note is that the error rate at 9600 b/s is almost double that at 4800 b/s.

Table 1

Data Summary - All Data

Data Rate	Total Bits	Total Errors	Bit Error Rate
4800 b/s	3,074,760,833	129,742	4.3 E-5
9600 b/s	3,996,064,721	325,130	8.1 E-5

The overall distributions of the error patterns have been summarized elsewhere [4] and will not be repeated here. Instead, an examination will be made of how block errors are distributed at the SATIN IV block length of 260 characters or 2080 bits. In figures 1 and 2 the distributions of consecutive block errors are presented for the 4800 and 9600 b/s data. At both data rates, it is possible to get large numbers of consecutive blocks each of which has at least one error. It should, however, be noted that at 4800 b/s, 99.9% of the errored consecutive blocks are less than a run of eight errored blocks [table 2a].* At 9600 b/s the equivalent length of a run of errored blocks is seven [table 2b]. Thus, while there can be very long runs of

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*For statistical purposes counting was in single units through 32 (shown in upper limit column) and grouped in powers of 2 above 32.

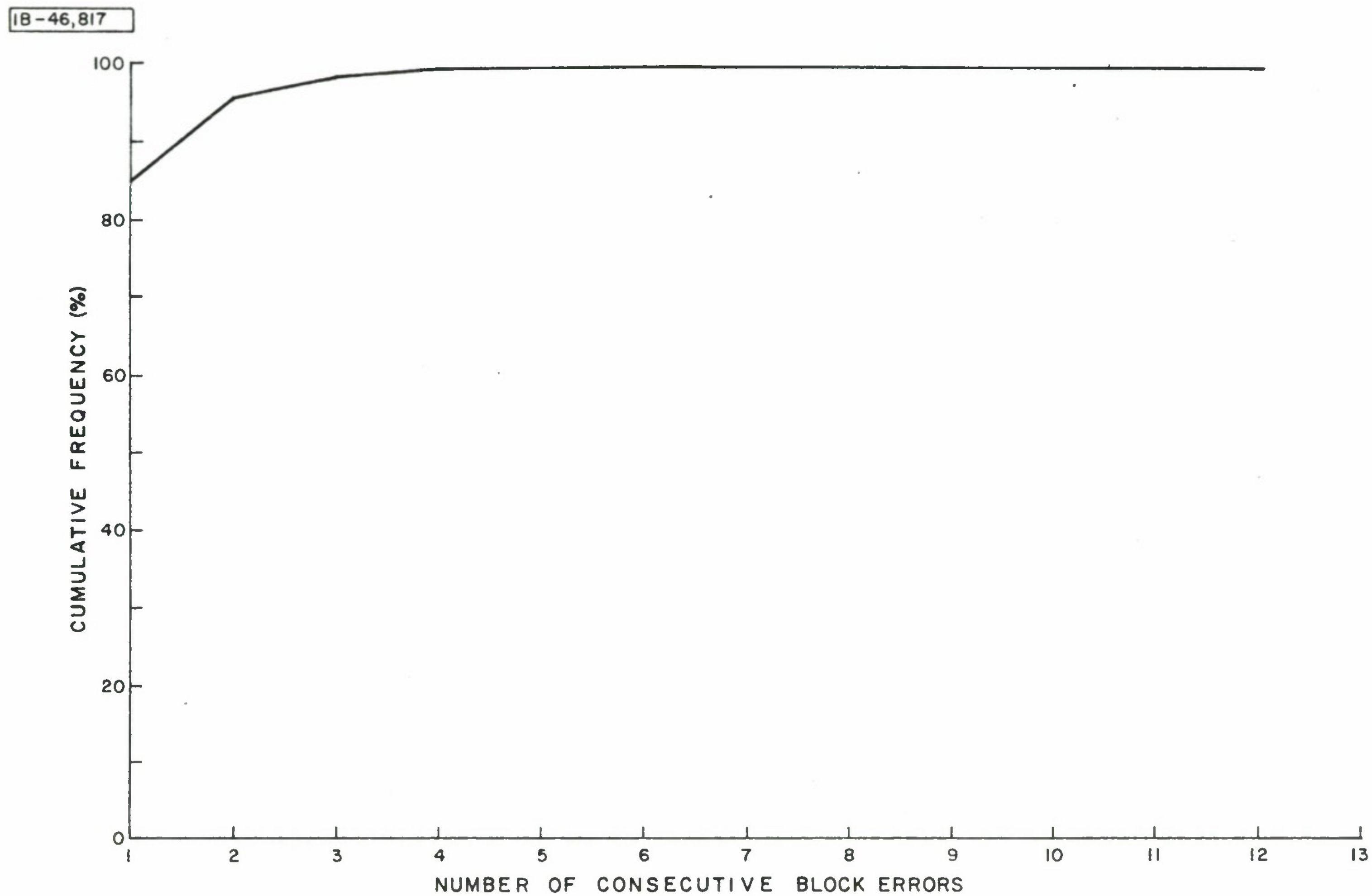

Figure 1 CULMULATIVE DISTRIBUTION OF CONSECUTIVE BLOCK ERRORS
4800 b/s DATA, 260 CHARACTER BLOCKS

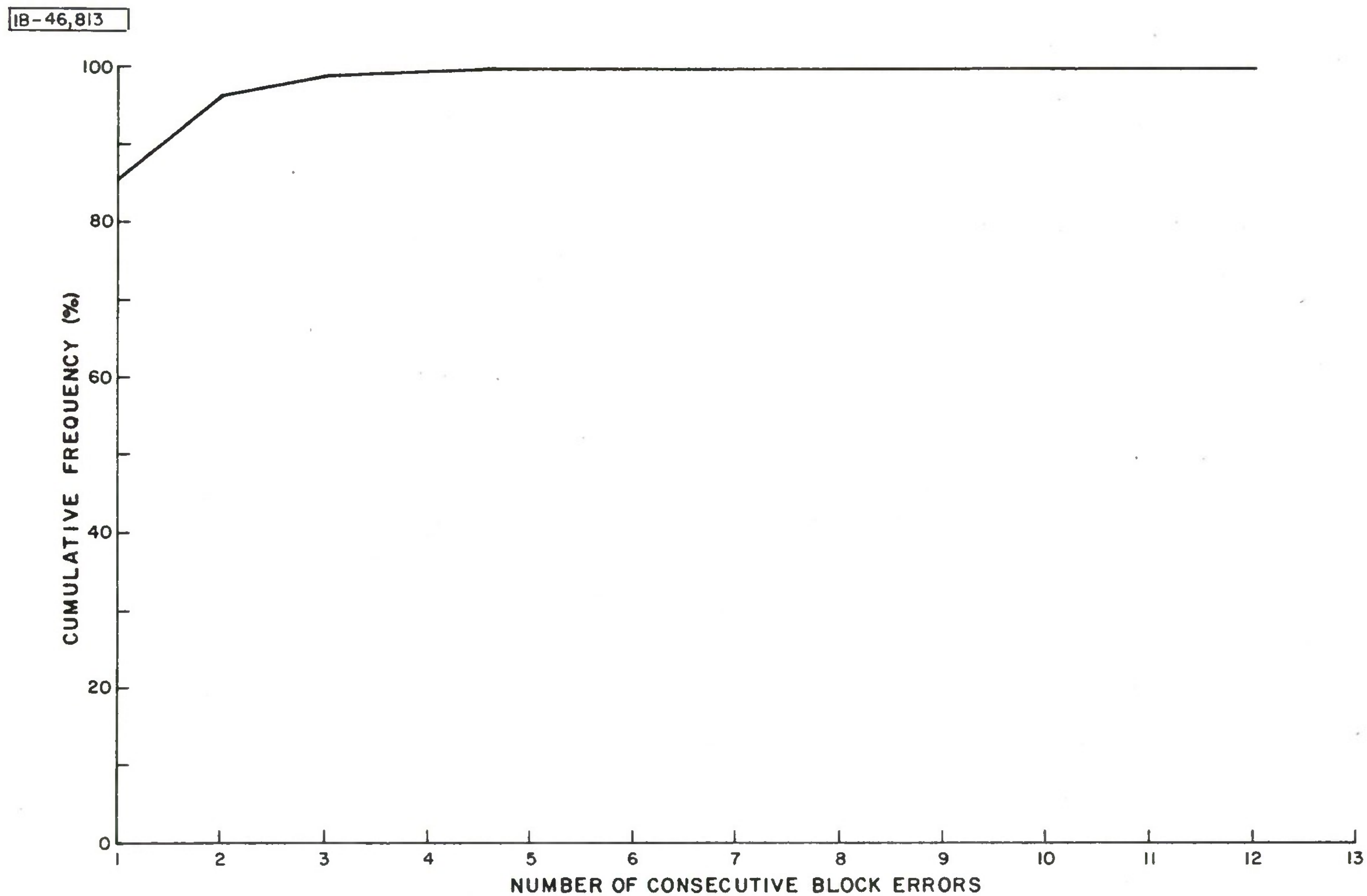

Figure 2 CUMULATIVE DISTRIBUTION OF CONSECUTIVE BLOCK ERRORS
9600 b/s DATA, 260 CHARACTER BLOCKS

Table 2 a) 4800 b/s

Distribution of Consecutive Block Errors

Lower Limit	Upper Limit	Frequency Distribution	Relative Frequency	Cumulative Frequency
	1	22597	84.928772	84.928772
	2	2851	10.715224	95.643997
	3	724	2.721087	98.365082
	4	250	0.939602	99.304688
	5	82	0.308190	99.612869
	6	42	0.157853	99.770721
	7	24	0.090202	99.860931
	8	16	0.060135	99.921066
	9	6	0.022550	99.943619
	10	6	0.022550	99.966156
	11	2	0.007517	99.973679
	12	3	0.011275	99.984955
	13	1	0.003758	99.988708
	14	3	0.011275	100.000000

Table 2 b) 9600 b/s

Distribution of Consecutive Block Errors

Lower Limit	Upper Limit	Frequency Distribution	Relative Frequency	Cumulative Frequency
	1	87424	85.398346	85.398346
	2	11160	10.901418	96.299759
	3	2498	2.440120	98.739883
	4	752	0.734576	99.474457
	5	287	0.280350	99.754807
	6	117	0.114289	99.869095
	7	41	0.040050	99.909149
	8	24	0.023444	99.932587
	9	15	0.014652	99.947235
	10	10	0.009768	99.957001
	11	5	0.004884	99.961899
	12	8	0.007815	99.969711
	13	2	0.001954	99.971664
	14	2	0.001954	99.973618
	15	1	0.000977	99.974594
	16	1	0.000977	99.975571
	17	2	0.001954	99.977524
	18	2	0.001954	99.979477
	19	3	0.002930	99.982407
	20	1	0.000977	99.983383
	21	1	0.000977	99.984360
	22	1	0.000977	99.985336
	23	1	0.000977	99.986313
	24	0	0.0	99.986313
	25	0	0.0	99.986313
	26	2	0.001954	99.988266
	27	3	0.002930	99.991196
	28	0	0.0	99.991196
	29	0	0.0	99.991196
	30	0	0.0	99.991196
	31	0	0.0	99.991196
	32	0	0.0	99.991196
33	64	9	0.008791	100.000000

errored blocks, such runs are rare and need not cause redialing in search of a new circuit. On figures 3 and 4 the distributions of error-free blocks between blocks are presented. Curves in the shape of these are usually indicative of bursts of errors. Thus, just as it has been shown [2] that bit errors occur in bursts, block errors also occur in bursts. Since the error-free distribution curve along with the consecutive error curve are fundamental to the development of many channel models, the data underlying figures 3 and 4 are included, for completeness, in table 3.

Another important statistic in determining whether or not to re-dial a circuit is the probability of exactly E block errors in an M block period of time P(E,M). As will be noted from figures 5 and 6, while P(E,M) increases with M, denoted as a super block, for periods of 1000 or more blocks there is little dependence on E. Since it is difficult to present complete detail on figures in the form of figures 5 and 6 the actual data is included as backup. Tables 4 through 14 present the 4800 b/s data. In following the data through these tables, it is interesting to note that while P(E,M) varies with E for small values of M this variation gradually disappears as M increases. However, as M increases, there are long periods of time occuring which contain large numbers of errored blocks. This is another demonstration of the burst nature of the channel. Similar results are seen in tables 15

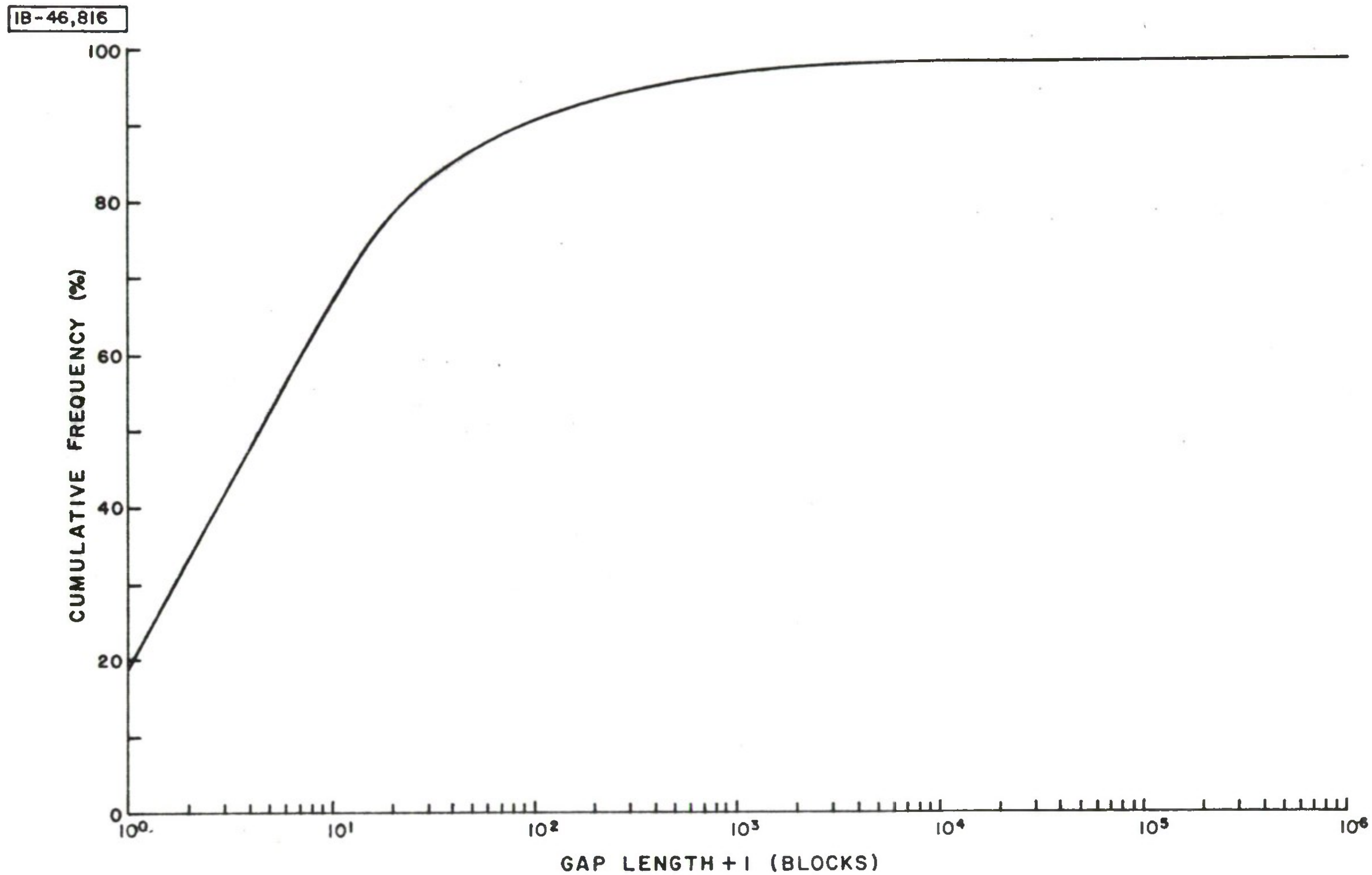

Figure 3 CUMULATIVE DISTRIBUTION OF ERROR FREE GAPS
4800 b/s DATA, 260 CHARACTER BLOCKS

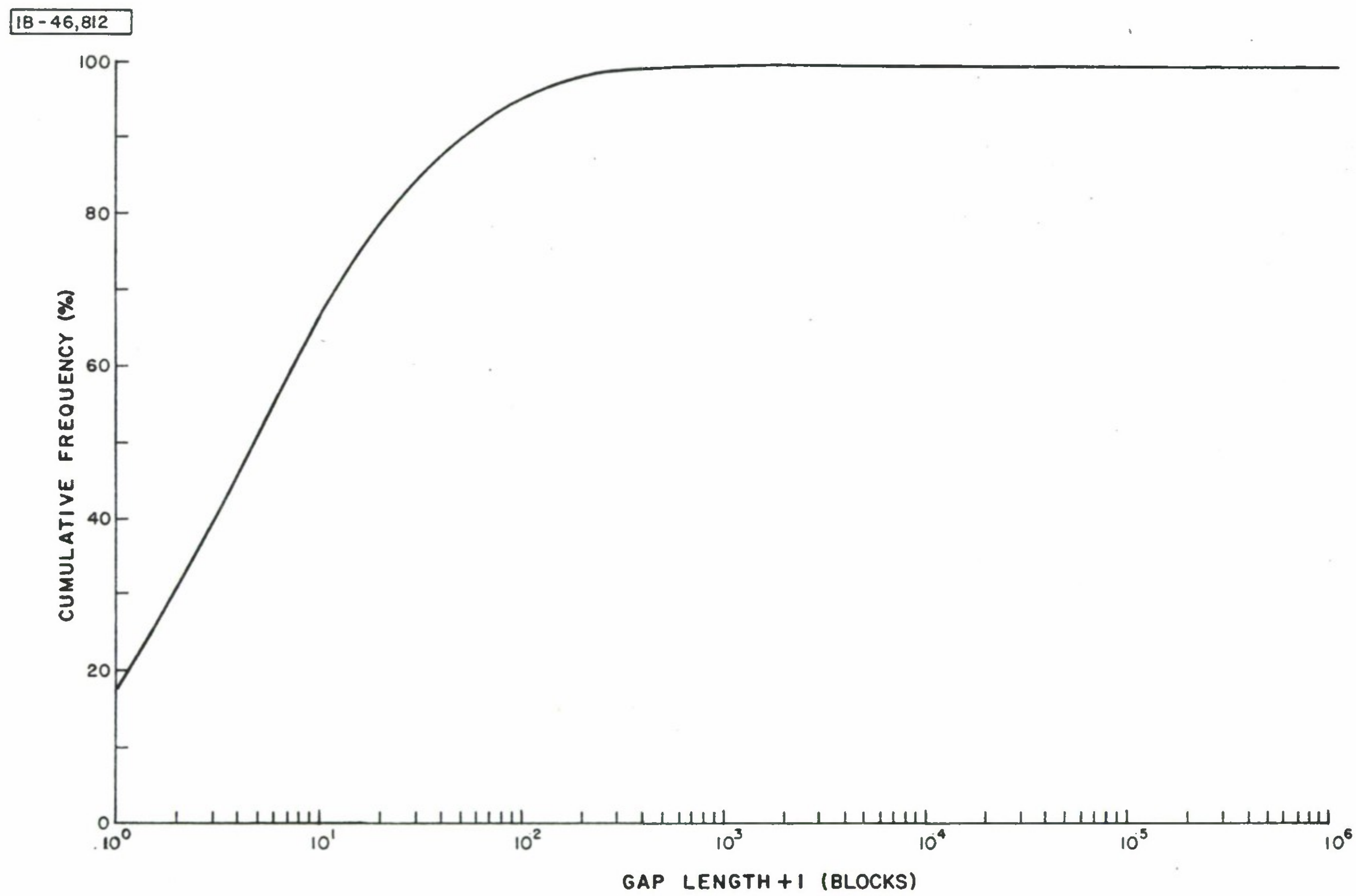

Figure 4 CUMULATIVE DISTRIBUTION OF ERROR FREE GAPS
9600 b/s DATA, 260 CHARACTER BLOCKS

Table 3 a) 4800 b/s

Distribution of Consecutive Error-Free Blocks

Lower Limit	Upper Limit	Frequency Distribution	Relative Frequency	Cumulative Frequency
	0	6049	18.523392	18.523392
	1	5014	15.353992	33.877380
	2	2586	7.918911	41.796295
	3	1984	6.075453	47.871750
	4	1490	4.562714	52.434464
	5	1178	3.607300	56.041763
	6	1133	3.469500	59.511261
	7	946	2.896864	62.408127
	8	916	2.804996	65.213120
	9	689	2.109872	67.322998
	10	560	1.714845	69.037842
	11	502	1.537236	70.575073
	12	452	1.384125	71.959198
	13	419	1.283072	73.242279
	14	394	1.206516	74.448792
	15	354	1.084027	75.532822
	16	278	0.851298	76.384109
	17	242	0.741058	77.125168
	18	256	0.783929	77.909103
	19	220	0.673689	78.582794
	20	209	0.640005	79.222794
	21	206	0.630818	79.853607
	22	186	0.569574	80.423187
	23	171	0.523640	80.946823
	24	149	0.456271	81.403107
	25	148	0.453209	81.856308
	26	124	0.379716	82.236023
	27	101	0.309285	82.545303
	28	119	0.364405	82.909714
	29	111	0.339907	83.249619
	30	101	0.309285	83.558899
	31	112	0.342969	83.901871
	32	84	0.257227	84.159103
33	64	1502	4.599461	88.758560
65	128	1006	3.080597	91.839157
129	256	826	2.529397	94.368561

Table 3a (concluded)

Distribution of Consecutive Error-Free Blocks

Lower Limit	Upper Limit	Frequency Distribution	Relative Frequency	Cumulative Frequency
257	512	592	1.812837	96.181396
513	1024	348	1.065654	97.247055
1025	2048	202	0.618569	97.865616
2049	4096	138	0.422587	98.288208
4097	8192	52	0.159236	98.447433
8193	16384	11	0.033684	98.481125
16385	32768	1	0.003062	98.484192
32769	65536	13	0.039809	98.524002
65537	131072	76	0.232729	98.756729
131073	262144	26	0.079618	98.836349
262145	524288	6	0.018373	98.854721
524289	1048576	22	0.067369	98.922089
1048577	Infinity	352	1.077903	100.000000

Table 3 b) 9600 b/s

Distribution of Consecutive Error-Free Blocks

Lower Limit	Upper Limit	Frequency Distribution	Relative Frequency	Cumulative Frequency
	0	21761	17.530243	17.530243
	1	16197	13.047995	30.578232
	2	10770	8.676106	39.254349
	3	8057	6.490565	45.744904
	4	6506	5.241110	50.986023
	5	5212	4.198688	55.184708
	6	4405	3.548584	58.733292
	7	3810	3.069263	61.802551
	8	3117	2.510996	64.313553
	9	2712	2.184735	66.498291
	10	2448	1.972062	68.470352
	11	2074	1.670774	70.141129
	12	1911	1.539465	71.680588
	13	1660	1.337264	73.017853
	14	1540	1.240594	74.258453
	15	1388	1.118146	75.376587
	16	1225	0.986837	76.363434
	17	1152	0.928029	77.291458
	18	1041	0.838610	78.130066
	19	1030	0.829748	78.959824
	20	909	0.732273	79.692093
	21	831	0.669438	80.361526
	22	802	0.646076	81.007599
	23	816	0.657354	81.664963
	24	747	0.601769	82.266724
	25	671	0.540545	82.807266
	26	656	0.528461	83.335739
	27	557	0.448709	83.784439
	28	554	0.446292	84.230728
	29	536	0.431791	84.662521
	30	551	0.443875	85.106400
	31	500	0.402790	85.509186
	32	494	0.397957	85.907150
33	64	8384	6.753990	92.661133
65	128	5181	4.173715	96.834854
129	256	2464	1.984951	98.819809

Table 3b (concluded)

Distribution of Consecutive Error-Free Blocks

Lower Limit	Upper Limit	Frequency Distribution	Relative Frequency	Cumulative Frequency
257	512	816	0.657354	99.477158
513	1024	243	0.195756	99.672913
1025	2048	129	0.103920	99.776840
2049	4096	53	0.042696	99.819534
4097	8192	48	0.038668	99.858200
8193	16384	5	0.004028	99.862228
16385	32768	0	0.0	99.862228
32769	65536	2	0.001611	99.863846
65537	131072	17	0.013695	99.877533
131073	262144	23	0.018528	99.896057
262145	524288	2	0.001611	99.897675
524289	1048576	11	0.008861	99.906540
1048577	Infinity	116	0.093447	100.000000

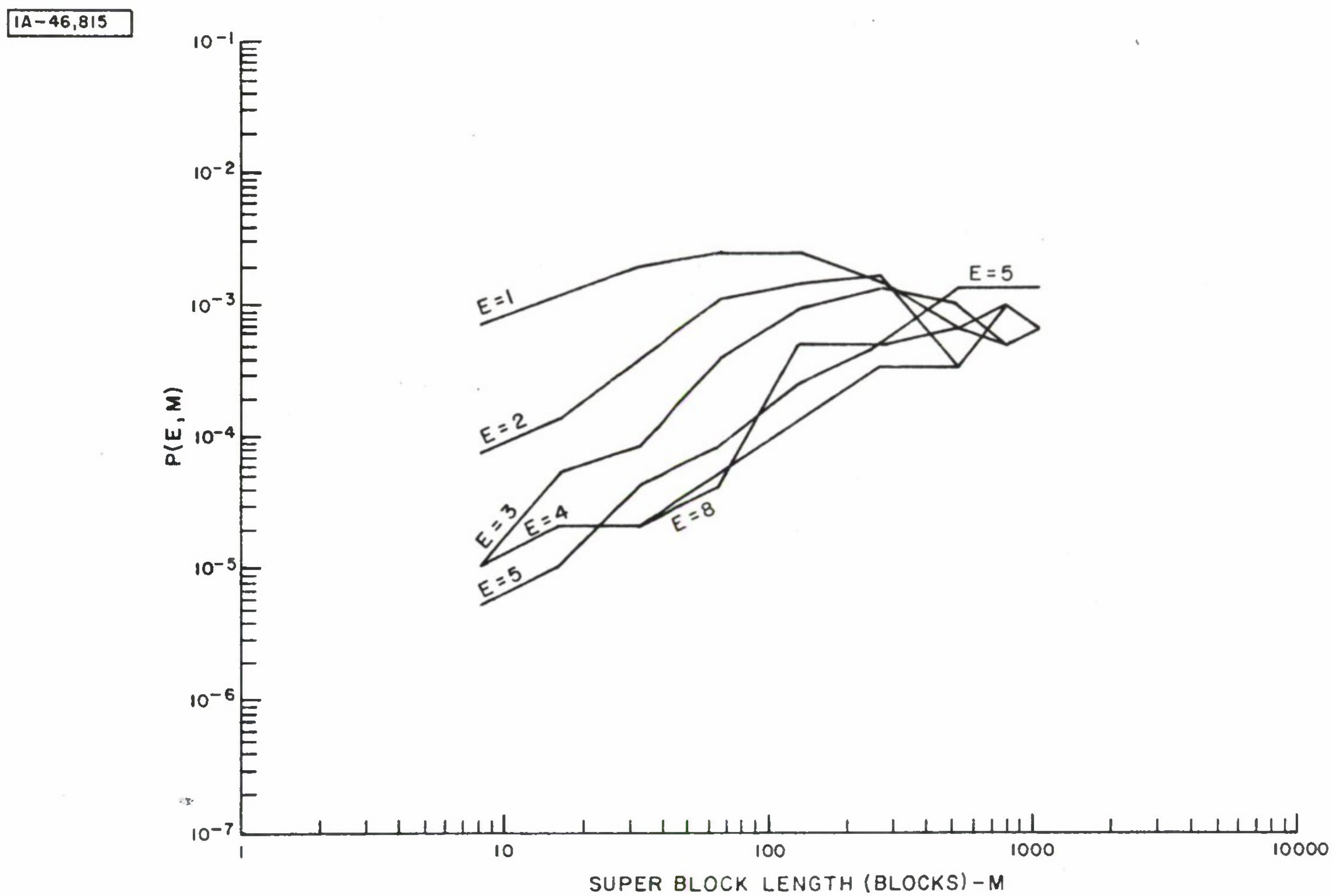

Figure 5 P(E,M) vs SUPER BLOCK LENGTH
4800 b/s DATA, 260 CHARACTER BLOCK

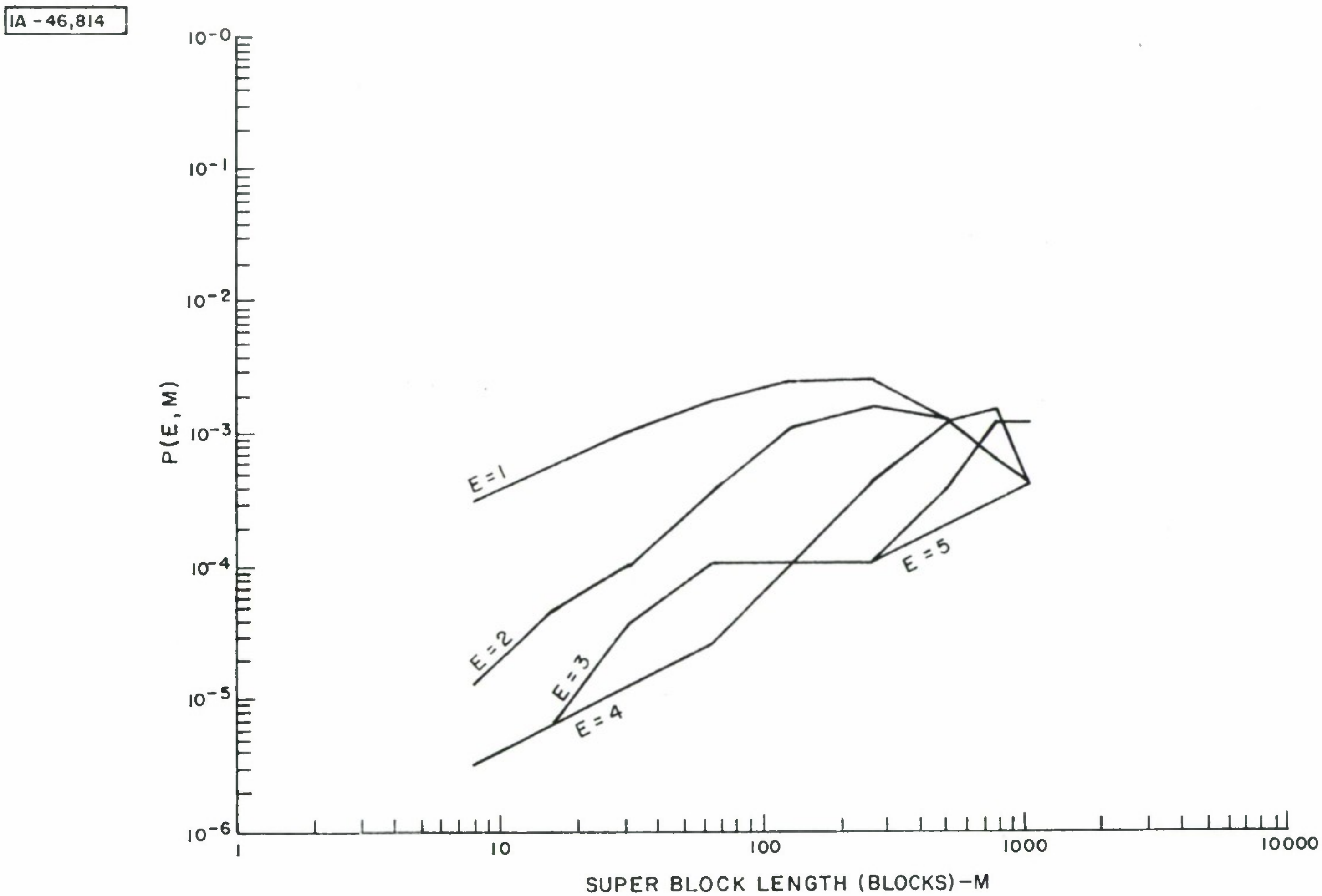

Figure 6 P(E,M) vs SUPER BLOCK LENGTH
9600 b/s DATA, 260 CHARACTER BLOCK

Table 4

Distribution of Block Errors in an 8 Block Period, 4800 b/s

No. of Errors	P(E,M)	Relative Frequency	Cumulative Frequency
1	7.20E–04	87.4172	87.4172
2	7.63E–05	9.2715	96.6887
3	1.09E–05	1.3245	98.0132
4	5.45E–06	0.6623	98.6755
5	1.09E–05	1.3245	100.0000

Table 5

Distribution of Block Errors in a 16 Block Period, 4800 b/s

No. of Errors	P(E,M)	Relative Frequency	Cumulative Frequency
1	1.23E–03	83.0882	83.0882
2	1.42E–04	9.5588	92.6470
3	5.45E–05	3.6765	96.3235
4	1.09E–05	0.7353	97.0588
5	2.18E–05	1.4706	98.5294
6	2.18E–05	1.4706	100.0000

Table 6

Distribution of Block Errors in a 32 Block Period, 4800 b/s

No. of Errors	P(E,M)	Relative Frequency	Cumulative Frequency
1	2.03E−03	76.8595	76.8595
2	3.92E−04	14.8760	91.7355
3	8.72E−05	3.3058	95.0413
4	4.36E−05	1.6529	96.6942
5	2.18E−05	0.8264	97.5206
7	2.18E−05	0.8264	98.3470
8	2.18E−05	0.8264	99.1735
11	2.18E−05	0.8264	100.0000

Table 7

Distribution of Block Errors in a 64 Block Period, 4800 b/s

No. of Errors	P(E,M)	Relative Frequency	Cumulative Frequency
1	2.53E−03	59.1837	59.1837
2	1.13E−03	26.5306	85.7143
3	3.92E−04	9.1837	94.8979
4	8.72E−05	2.0408	96.9388
5	4.36E−05	1.0204	97.9592
15	8.72E−05	2.0408	100.0000

Table 8

Distribution of Block Errors in a 128 Block Period, 4800 b/s

No. of Errors	P(E,M)	Relative Frequency	Cumulative Frequency
1	2.62E–03	42.8571	42.8571
2	1.48E–03	24.2857	67.1428
3	9.59E–04	15.7143	82.8571
4	2.62E–04	4.2857	87.1428
5	5.23E–04	8.5714	95.7142
6	8.72E–05	1.4286	97.1428
17	8.72E–05	1.4286	98.5714
18	8.72E–05	1.4286	100.0000

Table 9

Distribution of Block Errors in a 256 Block Period, 4800 b/s

No. of Errors	P(E,M)	Relative Frequency	Cumulative Frequency
1	1.57E–03	20.4545	20.4545
2	1.74E–03	22.7273	43.1818
3	1.40E–03	18.1818	61.3636
4	5.23E–04	6.8182	68.1818
5	5.23E–04	6.8182	75.0000
6	6.98E–04	9.0909	84.0909
7	3.49E–04	4.5455	88.6363
8	3.49E–04	4.5455	93.1817
23	3.49E–04	4.5455	97.7272
132	1.74E–04	2.2727	100.0000

Table 10

Distribution of Block Errors in a 512 Block Period, 4800 b/s

No. of Errors	P(E,M)	Relative Frequency	Cumulative Frequency
1	6.98E–04	7.4074	7.4074
2	3.49E–04	3.7037	11.1111
3	1.05E–03	11.1111	22.2222
4	1.40E–03	14.8148	37.0370
5	6.98E–04	7.4074	44.4444
6	1.05E–03	11.1111	55.5555
7	6.98E–04	7.4074	62.9629
8	3.49E–04	3.7037	66.6666
9	6.98E–04	7.4074	74.0740
10	3.49E–04	3.7037	77.7777
11	3.49E–04	3.7037	81.4814
13	3.49E–04	3.7037	85.1851
24	3.49E–04	3.7037	88.8887
25	3.49E–04	3.7037	92.5924
132	3.49E–04	3.7037	96.2961
276	3.49E–04	3.7037	100.0000

Table 11

Distribution of Block Errors in a 768 Block Period, 4800 b/s

No. of Errors	P(E,M)	Relative Frequency	Cumulative Frequency
1	5.23E-04	5.0000	5.0000
3	5.23E-04	5.0000	10.0000
5	1.05E-03	10.0000	20.0000
6	1.05E-03	10.0000	30.0000
7	1.05E-03	10.0000	40.0000
8	1.05E-03	10.0000	50.0000
12	1.05E-03	10.0000	60.0000
14	5.23E-04	5.0000	65.0000
15	5.23E-04	5.0000	70.0000
16	5.23E-04	5.0000	75.0000
26	5.23E-04	5.0000	80.0000
29	5.23E-04	5.0000	85.0000
132	5.23E-04	5.0000	90.0000
276	5.23E-04	5.0000	95.0000
698	5.23E-04	5.0000	100.0000

Table 12

Distribution of Block Errors in a 1024 Block Period, 4800 b/s

No. of Errors	P(E,M)	Relative Frequency	Cumulative Frequency
1	6.97E-04	5.8824	5.8824
4	1.39E-03	11.7647	17.6470
5	6.97E-04	5.8824	23.5294
7	6.97E-04	5.8824	29.4117
8	6.97E-04	5.8824	35.2941
9	6.97E-04	5.8824	41.1764
10	6.97E-04	5.8824	47.0587
15	6.97E-04	5.8824	52.9411
18	6.97E-04	5.8824	58.8234
19	6.97E-04	5.8824	64.7058
21	6.97E-04	5.8824	70.5881
28	6.97E-04	5.8824	76.4704
31	6.97E-04	5.8824	82.3528
132	6.97E-04	5.8824	88.2351
276	6.97E-04	5.8824	94.1175
698	6.97E-04	5.8824	100.0000

Table 13

Distribution of Block Errors in a 2048 Block Period, 4800 b/s

No. of Errors	P(E,M)	Relative Frequency	Cumulative Frequency
1	1.39E-03	7.6923	7.6923
5	1.39E-03	7.6923	15.3846
12	1.39E-03	7.6923	23.0769
16	1.39E-03	7.6923	30.7692
25	2.79E-03	15.3846	46.1538
47	1.39E-03	7.6923	53.8461
49	1.39E-03	7.6923	61.5385
132	1.39E-03	7.6923	69.2308
276	1.39E-03	7.6923	76.9231
698	1.39E-03	7.6923	84.6154
1678	1.39E-03	7.6923	92.3077
1999	1.39E-03	7.6923	100.0000

Table 14

Distribution of Block Errors in a 4096 Block Period, 4800 b/s

No. of Errors	P(E,M)	Relative Frequency	Cumulative Frequency
1	2.79E-03	10.0000	10.0000
5	2.79E-03	10.0000	20.0000
37	2.79E-03	10.0000	30.0000
63	2.79E-03	10.0000	40.0000
74	2.79E-03	10.0000	50.0000
132	2.79E-03	10.0000	60.0000
276	2.79E-03	10.0000	70.0000
698	2.79E-03	10.0000	80.0000
1678	2.79E-03	10.0000	90.0000
1999	2.79E-03	10.0000	100.0000

through 25 which are the 9600 b/s backup data.

Summary

It can be concluded that blocks in error occur in bursts, some of which are of high density, E/M. However, it is also concluded that 99.9% of the short duration bursts of consecutive errored blocks are in the order of 4 seconds long at 4800 b/s and 2 seconds long at 9600 b/s. Thus a short term burst of errored blocks would be past before re-dialing could be initiated. This fact along with the stability that occurs in long term block error performance would appear to mitigate against re-dialing AUTOVON circuits on the basis of block error rate alone.

Table 15

Distribution of Block Errors in an 8 Block Period, 9600 b/s

No. of Errors	P(E,M)	Relative Frequency	Cumulative Frequency
1	3.22E−04	94.1176	94.1176
2	1.34E−05	3.9216	98.0392
3	3.35E−06	0.9804	99.0196
5	3.35E−06	0.9804	100.0000

Table 16

Distribution of Block Errors in a 16 Block Period, 9600 b/s

No. of Errors	P(E,M)	Relative Frequency	Cumulative Frequency
1	6.04E−04	90.9091	90.9091
2	4.69E−05	7.0707	97.9798
3	6.71E−06	1.0101	98.9899
5	6.71E−06	1.0101	100.0000

Table 17

Distribution of Block Errors in a 32 Block Period, 9600 b/s

No. of Errors	P(E,M)	Relative Frequency	Cumulative Frequency
1	1.10E–03	84.5361	84.5361
2	1.07E–04	8.2474	92.7835
3	4.02E–05	3.0928	95.8763
5	1.34E–05	1.0309	96.9072
18	1.34E–05	1.0309	97.9381
20	1.34E–05	1.0309	98.9690
26	1.34E–05	1.0309	100.0000

Table 18

Distribution of Block Errors in a 64 Block Period, 9600 b/s

No. of Errors	P(E,M)	Relative Frequency	Cumulative Frequency
1	1.80E–03	75.2809	75.2809
2	3.76E–04	15.7303	91.0112
3	1.07E–04	4.4944	95.5056
5	2.68E–05	1.1236	96.6292
18	2.68E–05	1.1236	97.7527
20	2.68E–05	1.1236	98.8763
26	2.68E–05	1.1236	100.0000

Table 19

Distribution of Block Errors in a 128 Block Period, 9600 b/s

No. of Errors	P(E,M)	Relative Frequency	Cumulative Frequency
1	2.58E–03	61.5385	61.5385
2	1.13E–03	26.9231	88.4615
3	1.07E–04	2.5641	91.0256
5	1.07E–04	2.5641	93.5897
6	5.37E–05	1.2821	94.8718
18	5.37E–05	1.2821	96.1538
20	5.37E–05	1.2821	97.4359
26	5.37E–05	1.2821	98.7179
74	5.37E–05	1.2821	100.0000

Table 20

Distribution of Block Errors in a 256 Block Period, 9600 b/s

No. of Errors	P(E,M)	Relative Frequency	Cumulative Frequency
1	2.68E–03	43.1034	43.1034
2	1.61E–03	25.8621	68.9655
3	4.29E–04	6.8966	75.8620
4	4.29E–04	6.8966	82.7586
5	1.07E–04	1.7241	84.4827
7	2.15E–04	3.4483	87.9310
8	1.07E–04	1.7241	89.6551
20	2.15E–04	3.4483	93.1034
26	1.07E–04	1.7241	94.8275
74	1.07E–04	1.7241	96.5517
132	1.07E–04	1.7241	98.2758
238	1.07E–04	1.7241	100.0000

Table 21

Distribution of Block Errors in a 512 Block Period, 9600 b/s

No. of Errors	P(E,M)	Relative Frequency	Cumulative Frequency
1	1.29E–03	17.1429	17.1429
2	1.29E–03	17.1429	34.2857
3	1.29E–03	17.1429	51.4286
4	8.58E–04	11.4286	62.8571
5	4.29E–04	5.7143	68.5714
6	2.15E–04	2.8571	71.4285
9	6.44E–04	8.5714	80.0000
10	2.15E–04	2.8571	82.8571
20	2.15E–04	2.8571	85.7142
24	2.15E–04	2.8571	88.5714
27	2.15E–04	2.8571	91.4285
74	2.15E–04	2.8571	94.2856
132	2.15E–04	2.8571	97.1427
238	2.15E–04	2.8571	100.0000

Table 22

Distribution of Block Errors in a 768 Block Period, 9600 b/s

No. of Errors	P(E,M)	Relative Frequency	Cumulative Frequency
2	1.61E–03	19.2308	19.2308
3	6.44E–04	7.6923	26.9231
4	9.66E–04	11.5385	38.4615
5	1.29E–03	15.3846	53.8461
6	6.44E–04	7.6923	61.5384
9	3.22E–04	3.8462	65.3846
10	3.22E–04	3.8462	69.2307
12	3.22E–04	3.8462	73.0769
13	3.22E–04	3.8462	76.9230
20	3.22E–04	3.8462	80.7692
25	3.22E–04	3.8462	84.6153
27	3.22E–04	3.8462	88.4615
74	3.22E–04	3.8462	92.3076
132	3.22E–04	3.8462	96.1537
238	3.22E–04	3.8462	100.0000

Table 23

Distribution of Block Errors in a 1024 Block Period, 9600 b/s

No. of Errors	P(E,M)	Relative Frequency	Cumulative Frequency
1	4.29E–04	4.1667	4.1667
2	4.29E–04	4.1667	8.3333
3	4.29E–04	4.1667	12.5000
4	8.58E–04	8.3333	20.8333
5	1.29E–03	12.5000	33.3333
6	4.29E–04	4.1667	37.5000
7	8.58E–04	8.3333	45.8333
8	4.29E–04	4.1667	50.0000
10	8.58E–04	8.3333	58.3333
14	8.58E–04	8.3333	66.6666
20	4.29E–04	4.1667	70.8333
24	4.29E–04	4.1667	74.9999
27	4.29E–04	4.1667	79.1666
74	4.29E–04	4.1667	83.3333
132	4.29E–04	4.1667	87.4999
238	4.29E–04	4.1667	91.6666
800	4.29E–04	4.1667	95.8332
942	4.29E–04	4.1667	100.0000

Table 24

Distribution of Block Errors in a 2048 Block Period, 9600 b/s

No. of Errors	P(E,M)	Relative Frequency	Cumulative Frequency
2	8.58E–04	5.5556	5.5556
8	8.58E–04	5.5556	11.1111
9	8.58E–04	5.5556	16.6667
10	2.58E–03	16.6667	33.3333
15	8.58E–04	5.5556	38.8889
17	8.58E–04	5.5556	44.4444
19	8.58E–04	5.5556	49.9999
20	8.58E–04	5.5556	55.5555
27	8.58E–04	5.5556	61.1110
29	8.58E–04	5.5556	66.6666
74	8.58E–04	5.5556	72.2221
132	8.58E–04	5.5556	77.7776
238	8.58E–04	5.5556	83.3332
800	8.58E–04	5.5556	88.8887
942	8.58E–04	5.5556	94.4443
1999	8.58E–04	5.5556	100.0000

Table 25

Distribution of Block Errors in a 4096 Block Period, 9600 b/s

No. of Errors	P(E,M)	Relative Frequency	Cumulative Frequency
2	1.72E–03	7.1429	7.1429
10	1.72E–03	7.1429	14.2857
18	1.72E–03	7.1429	21.4286
20	1.72E–03	7.1429	28.5714
28	1.72E–03	7.1429	35.7143
29	1.72E–03	7.1429	42.8571
32	1.72E–03	7.1429	50.0000
37	1.72E–03	7.1429	57.1428
74	1.72E–03	7.1429	64.2857
132	1.72E–03	7.1429	71.4285
238	1.72E–03	7.1429	78.5714
800	1.72E–03	7.1429	85.7142
942	1.72E–03	7.1429	92.8571
1999	1.72E–03	7.1429	100.0000

SECTION III

MARKOV CHANNEL MODEL

The channel data collected is very useful for evaluating the performance of various error detection and/or correction techniques that might be applied to the channel. It is also useful in developing simulations which require channel information. Unfortunately, the raw channel data is only useful to those who have access to it along with large amounts of computer time and sophisticated computer programs. It is, however, possible to represent the data by a mathematical channel model and use this model for direct calculations and in a simulation. One such model is the MARKOV chain model.

The MARKOV Chain Model

Consider a series of discrete time outputs y_k of the digital communication channel to be the resultant summation of the inputs x_k and the noise n_k. Assume that the noise is independent of the input x_k. Since the noise and, in turn, the error sequence, is assumed to be independent of the input sequence, the channel may be completely characterized by its error sequence $E = (e_k : k=1, 2, \ldots)$. The error sequence is a bit stream of 0's and 1's where an error bit is represented by a 1, and an error-free bit is represented by a 0.

A distribution function which can be calculated from such an error sequence is the error-free run distribution, $P(0^m | 1)$. This distribution is the conditional probability that an error will be followed by at least m consecutive error-free bits. The error-free run distribution is used to obtain the channel model. In obtaining the model, it is further assumed that the error sequence has a limited number of states and the probability of being in any particular state at the Nth bit decision is conditionally dependent only upon the state during the (N-1)th bit decision. Such a process is called a MARKOV process of order one and can be represented by an N state MARKOV chain.

Fritchman [5] has developed a model for an N state MARKOV chain that partitions the N states into two groups of states, A and B. The $K (K < N)$ states in group A correspond to K states where errors cannot occur. The N-K states in group B correspond to the states in which errors can occur. In order to simplify the mathematics, Fritchman made two restrictions on the model. First, he did not allow transitions among the error states or among the error-free states. Second, he limited the model to a single error state, $K = N-1$. The state transition matrix for the MARKOV chain then becomes:

$$
T = \begin{bmatrix}
p_{11} & 0 & \cdots & & p_{1N} \\
0 & p_{22} & \cdots & & p_{2N} \\
\vdots & \vdots & \ddots & & \vdots \\
\vdots & \vdots & & p_{N-1,N-1} & \vdots \\
p_{N1} & p_{N2} & \cdots & p_{N,N-1} & p_{N,N}
\end{bmatrix}
$$

where p_{ij} is the probability of transition from state i to state j. Fritchman has shown that, for this model, the p_{ij} can be uniquely determined from the error-free run distribution, since for a stochastic matrix, $\sum_{j=1}^{N} P_{ij} = 1$, $i = 1, 2, \ldots, N$, there are only $2(N-1) = 2K$ unknowns. By fitting a sum of K exponentials to the error-free run distribution, the 2K unknowns may be determined. If the error-free run distribution can be approximated by

$$P(0^m \mid 1) = A_1 e^{a_1(m)} + A_2 e^{a_2(m)} + \ldots + A_K e^{a_K(m)}$$

then, Fritchman has shown that the transition matrix is given by

$$T = \begin{bmatrix} e^{a_1} & 0 & \cdots & & & 1-e^{a_1} \\ 0 & e^{a_2} & \cdots & & & 1-e^{a_2} \\ \vdots & & \ddots & & & \vdots \\ \vdots & & & e^{a_K} & & 1-e^{a_K} \\ A_1 e^{a_1} & A_2 e^{a_2} & \cdots & A_K e^{a_K} & & 1-\sum_{j=1}^{K} A_j e^{a_j} \end{bmatrix}$$

The values of the terms in the matrix are determined by applying a computer program to determine the values of the A's and a's that best fit the data error-free run distribution. The program starts by assuming a two state model (K=1) and increments K until a fit to the data error-free run distribution is achieved by the exponential polynomial expression. In practice an infinite number of states will fit any error-free run distribution. Therefore, some error criterion is usually set to limit the number of states.

Data-Derived Channel Models

The error-free run distributions for the 4800 and 9600 b/s data were fitted by sums of exponentials and the state transition matrices were calculated. The results are presented in Models 1 and 2. Since there is only one error state, K = N-1, the conditional probability of error is the probability p_N of being in state N, and an average bit error probability is found to be given by

$$p_e \cong \left[1 + \sum_{j=1}^{N-1} \frac{p_{N_j}}{p_{jN}} \right]^{-1}$$

with exact equality for a doubly stochastic matrix. For each of the transition matrices, the bit-error probability is given for the model, and the goodness of the fit of the model is reported.

In both cases, the RMS error between the data error-free run distribution and the model-predicted distribution was restricted to be less than .10, and the model was validated to that level of RMS error by using the model to generate error pattern data and comparing the error-free run distribution functions to those of the raw data.

MODEL 1

4800 b/s AUTOVON Data

$$\begin{bmatrix} .9996990 & 0 & .0003010 \\ 0 & .9999974 & .0000026 \\ .3669279 & .0443345 & .5887375 \end{bmatrix}$$

Model predicted error rate = 5.26 E-5

RMS error between model and data error-free run distributions = .088

MODEL 2

9600 b/s AUTOVON Data

$$\begin{bmatrix} .8656363 & 0 & 0 & .1343637 \\ 0 & .9994334 & 0 & .0005666 \\ 0 & 0 & .9999943 & .0000057 \\ .3668136 & .1796088 & .0640107 & .3895669 \end{bmatrix}$$

Model predicted error rate = 8.65 E-5

RMS error between mdoel and data error-free run distributions = .095.

Block Channel Model

Fritchman [5] also shows that the transition model for block errors , T_B, can be obtained from the transition model for bit errors,

$$T_B = T^B$$

where B is the block length in bits.
Since there are 260 eight bit characters in a block, B = 2080 bits. Thus it is only necessary to raise the two channel models to the 2080 power to obtain a model which directly predicts transitions between states which represent the occurrence or non-occurrence of block errors. Such models could be used, for example, in a network simulation where everytime a block transmission is simulated a random coin is flipped and depending on whether or not the block channel model enters the error state a block error requiring retransmission is or is not declared.

The matrices, T, are raised to the 2080th power by repeated squaring of the squares of the matrix. That is, if the matrix is squared and this product is squared and the procedure is performed eleven times the matrix has been raised to the 2048th power.

The fifth squaring achieves the 32nd power and this partial result is multiplied by the other result to achieve the 2080th power. Thus, only twelve matrix multiplies are needed to reach the 2080th power. These block error MARKOV transition matrices are presented as models 3 and 4.

MODEL 3

4800 b/s Block Matrix

.9343195	.0649960	.0006842
.0046465	.9953437	.0000096
.8341644	.1652235	.0006116

MODEL 4

9600 b/s Block Matrix

.0034879	.5430211	.4522146	.0012762
.9946765	.7314908	.2621213	.0017111
.0001099	.0073990	.9924506	.0000403
.0034842	.5424373	.4528034	.0012749

SECTION IV

THROUGHPUT RATE

An important parameter of any communications system is the link throughput rate. This rate is a measure of the efficiency of utilization of channel capacity of a communication system.

The throughput rate (R) is given by

$$R = \frac{\text{number of information bits transmitted in a block}}{\text{total number of bits transmitted before accepting the block}}$$

$$= \frac{k}{n + n\,P(\geq 1,n) + n\,[P(\geq 1,n)]^2 + \ldots.}$$

$$= \frac{k\,[1-P(\geq 1,n)]}{n}$$

where there are k information bits in a block

n total bits in the block

and $P(\geq 1,n)$ is the probability of at least 1 error in an n bit block, i.e., the block error rate.

Throughput rate is impacted by the fraction of the block which conveys no information, $(n-k)/n$, and the probability that the block will be in error and thus will be retransmitted, $P(\geq 1,n)$.

The overall throughput rate has been calculated using the block error probability information of Brayer [2] and is presented in figure 7. In performing this calculation the expected SATIN IV values of 22 overhead characters plus 4 cyclic redundancy check (CRC) characters per block have been assumed. Any message overhead that would be included in a multiblock message has been assumed part of the information. At both data rates a definite optimum block length occurs. At 9600 b/s it is B=3900 bits and at 4800 b/s it is B=9000 bits. At block lengths shorter than the optimum the overhead is the prime factor in reducing the throughput rate while at longer than optimum block lengths the retransmissions caused by errored blocks reduce the throughput rate. It should be noted that if the block length were 9000 bits the throughput rate at 9600 b/s would be virtually unchanged from that achieved at the 2080 bit block length chosen for SATIN IV. If the block length were increased to 3900 bits the 9600 b/s channel performance would be optimized and the 4800 b/s performance would be very near optimum.

For any of the test runs it is possible to simulate the performance of a retransmission error control system using that run as the channel. In table 26, the results of such a simulation are

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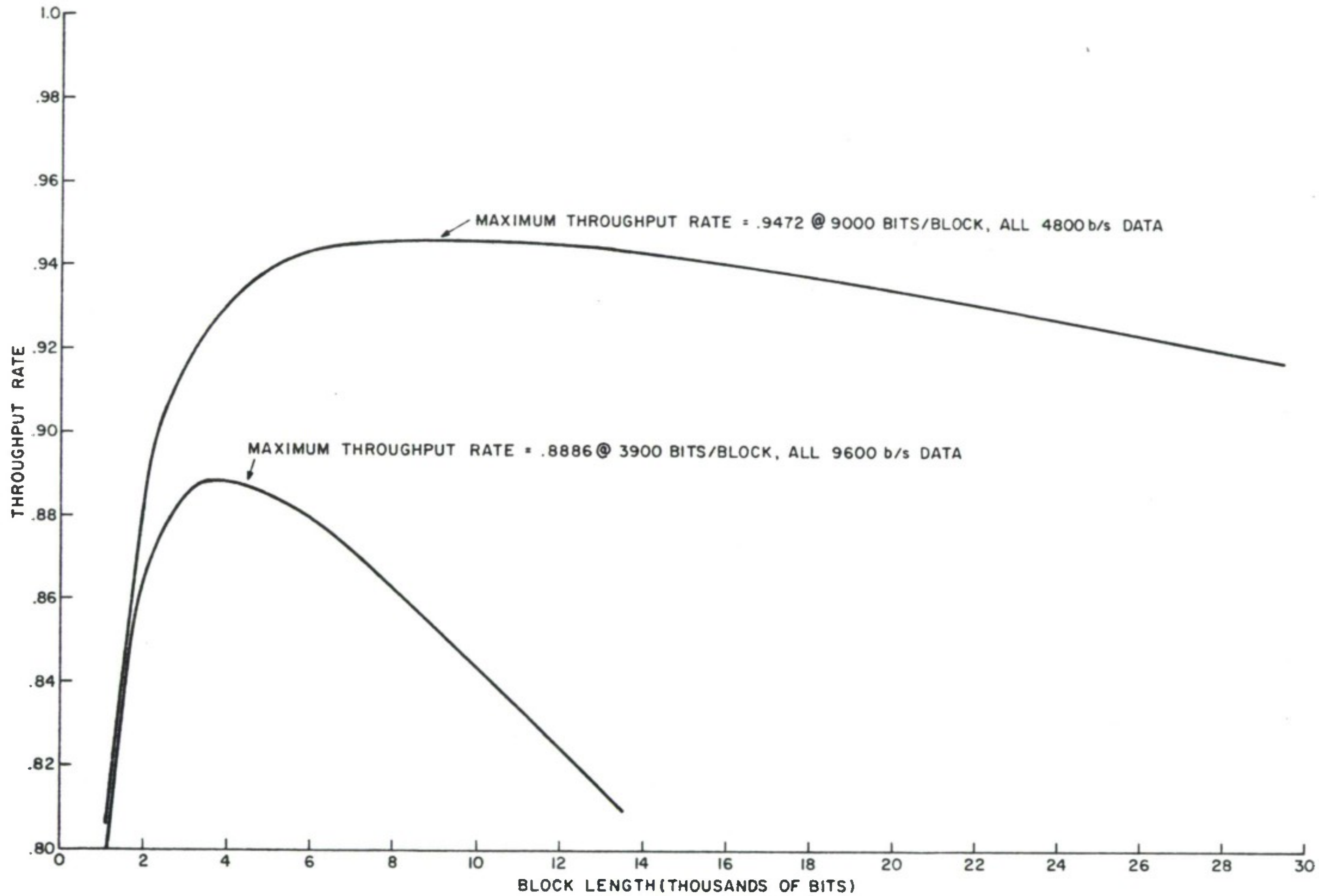

Figure 7 THROUGHPUT RATE vs BLOCK LENGTH
22 OVERHEAD CHARACTERS/ BLOCK,
4 CRC CHARACTERS/BLOCK

Table 26

Typical ARQ Link Performance Vs Block Length

	Block Length (characters)				
	100	200	300	400	500
Throughput					
4800 b/s	0.711	0.805	0.811	0.802	0.777
9600 b/s	0.694	0.772	0.768	0.746	0.731
Number of Retransmissions					
4800 b/s	196	165	164	159	166
9600 b/s	647	524	496	488	451

Note: 10 minute transmission time, 22 header characters/block, 4 CRC characters/block, 8 bits/character.

presented using two poorer than average (i.e., higher error rate) test samples, one at 4800 b/s and one at 9600 b/s. In both cases, the optimum block length is rather broad in its range of values just as in the case of the total data sample. As can be seen from table 27, throughput rate is fairly constant with transmission time and barring any short bursts of retransmissions, the number of retransmissions is approximately proportional to transmission time. This again shows the long term stability of AUTOVON retransmission performance and mitigates against frequent changing of circuits, based only on high block error rates.

Table 27

Typical ARQ Link Performance Vs Transmission Time

	Transmission Time (minutes)					
	0.25	0.50	1.00	2.50	5.00	10.00
Throughput						
4800 b/s	0.833	0.845	0.839	0.819	0.816	0.814
9600 b/s	0.806	0.725	0.735	0.730	0.753	0.777
Number of Retransmissions						
4800 b/s	3	5	11	38	79	163
9600 b/s	9	37	69	178	300	487

Note: 260 characters/block, 22 header characters/block, 4 CRC characters/block, 8 bits/character.

SECTION V

CONCLUSIONS

This paper has addressed three subjects:

- Distributions of Block Errors
- Block Error Channel Modeling
- Throughput Rate

Distributions of Block Errors

It has been demonstrated that just as bit errors occur in bursts on the AUTOVON channel, block errors occur in bursts. Of these bursts 99.9% of those consecutive blocks that are in error occur for less than 4 seconds at 4800 b/s (2 seconds at 9600 b/s). As such the short term bursts terminate too quickly to make circuit re-dialing an approach to avoiding them. In fact, the long term distribution of these bursts of block errors is of sufficient homogeniety as to preclude the possibility of avoiding these bursts by re-dialing. Lemon [3] claimed that AUTOVON was not suitable for data transmission because of the error rates observed and his numerical results have been duplicated by this author [2]. Thus, the perceived AUTOVON block errors appear unavoidable by SATIN IV if AUTOVON is used.

Block Error Channel Model

For those interested in simulating communication performance on AUTOVON a model has been developed for predicting the occurrence of block errors. While it was developed for 2080 bits per block the technique can be used for any block length.

Throughput Rate

A throughput analysis has been performed and it has been demonstrated that the optimum block length for efficient use of the communications channel is between 3900 and 9000 bits. Including overhead and retransmissions not less than 5% nor more than 11% of the communication channel capacity for data need be wasted. At the SATIN IV block length of 2080 bits there is a slight increase in inefficiency of channel utilization (3 to 7%) but since retransmissions will occur less frequently the response time of delivering messages should be enhanced.

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