AD-A107 886 DEFENSE COMMUNICATIONS ENGINEERING CENTER RESTON VA F/G 17/2
A MEASURE OF EFFECTIVENESS - ANALYSIS AND APPLICATION.(U)
JUN 81 R PODELL
UNCLASSIFIED DCEC-TN-12-81 NL

1 of 1
AD
A107886

END
DATE
FILMED
1-82
DTIC

4

LEVEL II

4

AD A107886

TN 12-81

DEFENSE COMMUNICATIONS ENGINEERING CENTER

TECHNICAL NOTE NO. 12-81

A MEASURE OF EFFECTIVENESS-ANALYSIS AND APPLICATION

JUNE 1981

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: DCEC-TN-12-81	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): A MEASURE OF EFFECTIVENESS - ANALYSIS AND APPLICATION	5. TYPE OF REPORT & PERIOD COVERED: TECHNICAL NOTE
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): ROBERT PODELL	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Defense Communications Engineering Center, Systems Engineering Division, R700, 1860 Wiehle Ave, Reston, VA 22090	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: N/A
11. CONTROLLING OFFICE NAME AND ADDRESS: Same as 9	12. REPORT DATE: Jun[redacted]81
	13. NUMBER OF PAGES: 35
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): N/A	15. SECURITY CLASS. (of this report): Unclassifed
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE: N/A

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

N/A

18. SUPPLEMENTARY NOTES

Review relevance 5 years from submission date.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Communications; Digital; Effectiveness; Voice communications; Data transmission systems; Defense systems; Defense Planning; Systems engineering, Probability; Mathematical models; Packets; Reliability; Delay

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

A measure of effectiveness (M.O.E.) for communications is formulated, in general, and applied to a digital path assuming: no queueing; independent poisson (long and/or short) failures and exponentially distributed repairs. The M.O.E., the probability of reliable information completion within a tolerable delay given an environment, is evaluated for cases without and with dynamic restoral of failures via repeat transmission. Response time vs. packet length is also modelled. Without dynamic restoral, shown are: reliability is a limiting factor; relative robustness of higher bit rates for voice. With dynamic restoral, the M.O.E.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED 407519

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. Abstract....

approaches 1 as delay approaches infinity.

RE: Classified References, Distribution Unlimited.
No Change per Ms. Donna Rhodes, DCEC/R141

TECHNICAL NOTE NO. 12-81

A MEASURE OF EFFECTIVENESS - ANALYSIS AND APPLICATION

JUNE 1981

Prepared by:

- Robert Podell

Approved for Publication:

G.E. LaVEAN
Chief, Systems Engineering Division

FOREWORD

The Defense Communications Engineering Center (DCEC) Technical Notes (TN's) are published to inform interested members of the defense community regarding technical activities of the Center, completed and in progress. They are intended to stimulate thinking and encourage information exchange; but they do not represent an approved position or policy of DCEC, and should not be used as authoritative guidance for related planning and/or further action.

Comments or technical inquiries concerning this document are welcome, and should be directed to:

Director
Defense Communications Engineering Center
1860 Wiehle Avenue
Reston, Virginia 22090

TABLE OF CONTENTS

		Page
	SUMMARY	v
I.	INTRODUCTION	1
II.	BACKGROUND	1
III.	TECHNICAL DISCUSSION	2
IV.	SIGNIFICANT FINDINGS AND CONCLUSIONS	21
	REFERENCES	22
	GLOSSARY OF TERMS	24
APPENDIX		
A	DERIVATION OF THE CDF OF DELAY XRS FOR AN N PACKET CASE	A-1

LIST OF ILLUSTRATIONS

Figure	Title	Page
1.	EFFECTIVENESS, NO DYNAMIC REPAIR	6
2.	EFFECTIVENESS, n PACKETS, EQ. (13)	20

LIST OF TABLES

Table	Title	Page
I.	VARIATION OF SHORT TERM VOICE MEAN FAILURE RATES (FS) AND REPAIR RATES (MS) WITH ERROR PROBABILITY (P) AND BIT RATE (B)	9
II.	DATA PERFORMANCE AS A FUNCTION OF ERROR PROBABILITY P	15
III.	VOICE PERFORMANCE AS A FUNCTION OF ERROR PROBABILITY P	17

SUMMARY

A key goal in planning/designing future WWDSA/DSN/DCS architectures/systems is to provide their C^2 subscribers, under varying environments/stress levels, an acceptably high probability of reliably completing their required information transfers within a time required for mission accomplishment. In support of this goal, a measure of effectiveness (M.O.E.) is formulated as the probability given an environment/stress level that a subscriber to subscriber information transfer is completed, reliably, within an acceptable delay. The M.O.E. is described for a general case but is only applied to two special cases assuming: a digital path; no queuing delays; all failure events are Poisson distributed; and all times to recover from failures are exponentially distributed. Furthermore, failure events include long term outages (>60 seconds) as well as short term (≤60 seconds) degradations of bit error rate which fall below an acceptable threshold for the mode used (voice or data).

In the first case studied, which is similar to AUTOVON overseas, probabilities are explicitly modelled for conditions where successful information transfers are prevented by failures (long/short) or delayed by the time needed to restore the path. Mean rates of short term failure and "repair" are developed as a function of bit rate (B) and average error probability (P). The parameters of the M.O.E. are shown to be long and short term average path "failure" and "repair" rates, as well as the average information transfer duration (1/M). (Information transfer durations are assumed to be exponentially distributed.) The M.O.E. parameters are changed to emulate the effects of increasing stress, and the endurability enhancements of faster acting tech control. In the context of DCS-tactical paths, the additional effects of changing P and B are also evaluated. Relative robustness of higher B for voice under degraded P is shown, and the need for higher data reliability. ITSTEC is shown to be a substantial improvement, but effectiveness will still be severely limited by short term reliability, for reliability averaged over the information transfer (average duration, 1/M) is shown to be asymptotic to $M/(M+F_L+F_S)$, where F_L and F_S are the mean long and short term failure rates.

The search for a more endurable system next considers the second case, dynamic "repair", of the form where information transfer attempts which fail are repeated, until reliably completed. Here, reliability (R) (neglecting undetected errors) is asymptotic to 1. Analysis of the case with long and short term parameters and variable information durations requires conversion from s to Z transforms for explicit time domain solution, and is not presented here. However, evaluation of the M.O.E. for this case is mathematically equivalent to finding the impulse response of an infinite impulse response (IIR) digital filter. Instead, the M.O.E. is derived for a constant information transfer duration with short term failures and "repairs", with and without dynamic "repairs". As the delay approaches infinity, $\Pr[\text{delay} \leq t] \times R$ approaches 1, with dynamic repair, and approaches R without it. Performance variation as a function of error probability, P, and measurement interval are studied, for data and voice, with and without dynamic repair. For voice the useful range of P is shown to be the same with and without repeats.

Finally, assuming short term Poisson failures and exponentially distributed repair times, and an n packet message of constant duration, an expression for the M.O.E. ($Pr(delay \leq t) \times R$) is derived and physically interpreted. The response time improvements of packetizing data are also shown.

In view of the poor reliability of no dynamic repair, and the intolerable delay of dynamic repair via repeat for voice, dynamic repair via fast switching deserves study and consideration.

I. INTRODUCTION

The purposes of this paper are to present a conceptual measure of effectiveness (M.O.E.) and to demonstrate that the M.O.E. can provide (a) a framework for imbedding many currently incoherent architectural bits and pieces, and (b) a focal point for measuring the contribution of a piece and viewing it in relationship to that of other pieces. This effort was done in support of the DCS Plan FY 90-95, and is intended to contribute to improved planning of future DCS and WWDSA architectures.

II. BACKGROUND

In support of the effort of recommending a future DCS architecture, current relevant architectural studies were reviewed and summarized, including: WWMCCS [1,2,3], WWSVA [4], WWDSA [5,6,7], DSN [8,9], ITSEC [10], IASA [11,12], EISN [13], and MILSATCOM/DSCS [14,15,16,17]. In attempting to summarize individually interesting features of each system, one rapidly loses sight of the forest for the trees. Therefore, it was decided to approach the problem of summarizing key architectural features by first constructing a picture of the forest (the M.O.E.) from its trees (elements of the M.O.E.), and then relating the architectural features observed to the M.O.E. elements.

III. TECHNICAL DISCUSSION

An architectural description of a system is viewed as a description sufficient to allow one to trace representative subscriber-to-subscriber(s) information transfer (i.t.) paths across subsystem and management boundaries. It should also permit an evaluation in some sense of the goodness of the i.t.

Consider that the fundamental purpose of a communications system is to provide transfer of information subscriber-to-subscriber(s), within a timeliness consistent with subscriber mission accomplishment. For if timeliness were not the key requirement, slower physical transport of the information could be employed.

At this point, a measure of goodness for a representative subscriber pair (or conference group) could be the probability that the information is transferred between (among) them within an acceptable delay. Such a probability could be estimated from a sample of representative subscriber pairs (groups), and over a suitable span of exogenous stress environments/stress levels. Other important factors such as quality/accuracy and security could be implicitly included in the sense that a sample is not scored as successful unless thresholds required for these factors are exceeded.

We obtain a quantitative expression for probability that the subscriber-to-subscriber information is reliably transferred within an acceptable delay, D, given an environment, Ei, explicitly modeling the probabilities that successful information transfers are either prevented by failures/accuracy degradations or delayed by time to restore. At this stage, we have omitted queueing effects in the explicit evaluations, but do indicate how such effects could be included using the distribution function of queueing delay, given that the path is available. In the following derivation, to simplify notation the given environment will be implicitly contained in the probability values assigned.

The initial model includes two mutually exclusive compound random events, namely,

$$[a + \overline{a}(re)]\ (W)\ T\ r \qquad (1)$$

Here, a is the event that the path is available at the instant of demand, $\overline{a}$ is the complement of a, re is the event that the path is restored/repaired within some time delay given it was not available $(\overline{a})$, r is the event that the path is reliable over interval T + W given it was available, where T is the information transfer interval and W is the waiting time on queue.

To obtain the probability of reliably completing the information transfer within acceptable delay D, one can find the probability density function (pdf) of the total delay for each of the compound events and integrate the pdf from 0 to D.

One can partition the availability, reliability, and repair events into long (L) and short (S) term components, i.e., > 1 minute and < or = to 1 minute, in accord with current engineering practice. This partitioning results in the following four compound events leading towards potential success:

$$[aL + (\overline{aL})(reL)][aS + (\overline{aS})(reS)]\ WT(rL)(rs). \qquad (2)$$

Dynamic repairs, i.e., repairs taking place during the information transfer interval, are discussed later in this TN. Two forms are: (a) Automatic Repeat Request (ARQ); and (b) use of redundancy with fast switching to enhance reliability/availability by sensing degradation on the path and switching in a replacement element prior to potential path failure. Only the ARQ case is discussed in this paper.

By way of physical explanation of a sample term from equation (2), consider the final term, which is

$$\overline{aL}\ reL\ \overline{aS}\ reS\ WT\ (rL)\ (rS).$$

This is the event that the path is not long term available ($\overline{aL}$), it is repaired (reL) thereby becoming available, but is not available short term ($\overline{aS}$), is repaired (reS), being now available waits on a queue a time (W), is of duration (T), and stays reliable long term (rL), and given that condition stays reliable short term (rS). The resulting delay incurred in completing such an event is reL + reS + W + T, where these are random variables, and by assumption are independent.

Since the total time delay to completion of the information transfer is the sum of a number of (by assumption) independent random variables, the probability density function (pdf) of the total time delay to completion is the convolution of the pdf's of the individual random variables. One can then obtain the corresponding probability that the total delay to completion is ≤ D, i.e., the cumulative distribution function (CDF) by integrating the pdf from time 0 to D. Finally, multiplying the CDF by the probability that the path does not fail over the information transfer interval T will result in a joint probability function which measures the probability that the information is completely transferred within time D, and the path does not fail over the information transfer interval T. We will let the queue wait W=0 in the ensuing analysis, in order to keep it more analytically tractable. We note that given a density function for the queue waiting time, and if independence still holds, queueing effects could be included.

Consider next term-by-term events and probabilities involved in the delay computation, omitting queue delays and excluding for now the reliability terms which are a common multiplier. The first such compound event in equation (2) is (aL)aS(T). Assuming the duration T is exponentially distributed with mean of $\bar{T} = 1/M$, the probability density function for this event is (AL)(AS)[Mexp(-MT)dT]. Here AL is the probability of event aL, or long term ($>$ or = 1 minute) availability. AL is estimated as 1-(sum total of outages $>$ or = to 1 minute duration divided by the total measurement interval). (Under a stress environment such outages could include those produced by enemy attack, hence survivability is implicitly included.) AS, the probability of event aS, is the short term ($<$ 1 minute) point availability, estimated as 1-(sum total of outages $<$ 1 minute duration divided by a total measurement interval which excludes outages whose duration are = or $>$ 1 minute). Thus AS is a measure of the probability of obtaining acceptable quality (i.e., for voice) or accuracy (i.e., for data) given the path is long term available. Integrating the pdf from T=0 to D produces a contribution to the CDF of (AL)(AS)[1-exp(-MD)].

The second compound event in equation (2) is $\overline{aL}$(reL)aS(T), with a pdf of (1-AL) U (t-1/60)[ML exp(-ML(t-1/60))dt] AS [Mexp(-MT)dT]. Here U(t-1/60) is a unit step function, value 0 for $t < 1/60$ hour, value 1 for $t >$ or = 1/60 hour. ML is the average repair/restoral rate of outages $>$ or = 1 minute, i.e., ML is 1/MTTR, where MTTR is the mean time to repair/restore the path in hours. The probability that the delay t+T is $<$ or =D, found by integrating the joint pdf over the region of the t,T plane bounded by t=1/60, T=0 and the line t+T=D, is

$$U(t-1/60)\ (1-AL)\ (AS)\ [1/(M-ML)][M(1-\exp[-ML(D-1/60)] - ML(1-\exp[-M(D-1/60)]].$$

The third compound event in equation (2) is aL($\overline{aS}$)reS(T). The resulting contribution to the CDF of delay is:

$$AL(1-AS)\ [1/(M-MS)]\ [M(1-\exp[-MSD])-MS(1-\exp[-MD]).$$

where an exponential pdf for short term repairs/restorals, mean rate MS, has been used. Strictly speaking, the conditional pdf for short term repairs $<$ 1 minute should be of the form

$$[1/(1-\exp(-b/60))]b\ \exp(-bt) \quad 0<t<1/60 \text{ hour},$$

0 for $t > 1/60$ hour, which produces an average short term repair time (in hours) of 1/b -(1/60) exp [-b/60]/(1-exp[-b/60]). For the average short term repair times subsequently derived and used in this report, which are at most a few seconds, exp (-b/60) $\ll$ 1/b and 1. Hence, using the density function MSexp(-MSt) $0 < t < \infty$ for values of 1/MS up to a few seconds has negligible effect on the results.

The fourth compound event in equation (2), $\overline{aL}(reL)\overline{aS}(reS)T$, produces a CDF of

$$U(D-1/60)(1-AL)(1-AS)(1/[MS-ML][M-ML][M-MS]) \times$$

$$(M[(M-MS)MS(1-\exp[-ML(D-1/60)])-(M-ML)ML(1-\exp[-MS(D-1/60)])] +$$

$$MLMS(MS-ML)(1-\exp[-M(D-1/60)])] .$$

Adding the four contributions to the CDF derived thus far produces the desired probability of delay to completion of the information transfer. At $D=\infty$, the CDF=1. For a given information transfer of duration T, the probability of compound event rLrS is assumed to be exp(-FLT) x exp (-FST). Here, long term failure rate FL is (1/mean time to fail) given the path was up at the start of any sample interval and counts only failures > 1 minute. Short term failure rate FS is similar but counts as failures only those involving measurement intervals < or = 1 minute. Since the probability of occurrence of T lying between T and T+dT is Mexp(-MT)dT, the average probability of not failing over interval T is

$$\int_0^\infty M\exp(-MT)\exp[-(FL+FS)T]dT=M/(M+FL+FS).$$

In most of the following derivations and curves we shall employ this average reliability value.

Figure 1 shows some representative plots of the product of the probability that the total delay < or =D, and the probability (averaged over T) that the path does not fail over its information transfer duration. The abscissa shows time delay in hours. The ordinate is the product of the probability that the information transfer is completed in a time < or = D and is reliable over its duration. The top curve is perfect performance, and is the $Pr[d \leq D] = 1-e^{-MD}$, the CDF of an exponentially distributed information transfer, mean duration of 1/M. This curve is a very useful benchmark against which to judge system performance. Noting that AL = 1/(1+FL/ML) and As=1/(1+FS/MS), and average reliability, R, is M/(M+FL+FS), perfect performance occurs at FL=FS=0. As F approaches ∞, i.e., zero mean time to failure (MTTF), the worst possible performance occurs, $Pr[d \leq D]=0$, which is the abscissa in Figure 1. Another noteworthy point is that, assuming highest precedence subscribers suffer no queueing delay, elimination of queueing delays in the current model makes it representative of delays to completion seen by highest precedence subscribers (for systems which do not repair/restore during the information transfer interval).

Next, using both experience and calculable theoretical models, values for FL, ML, FS and MS are derived. These values can be associated with various environments and system designs. Their impact on performance is examined by plotting the $Pr[d \leq D] \times R$. Let us start with a model for a current overseas digital AUTOVON DCS. Consider first the long term parameters FL and ML.

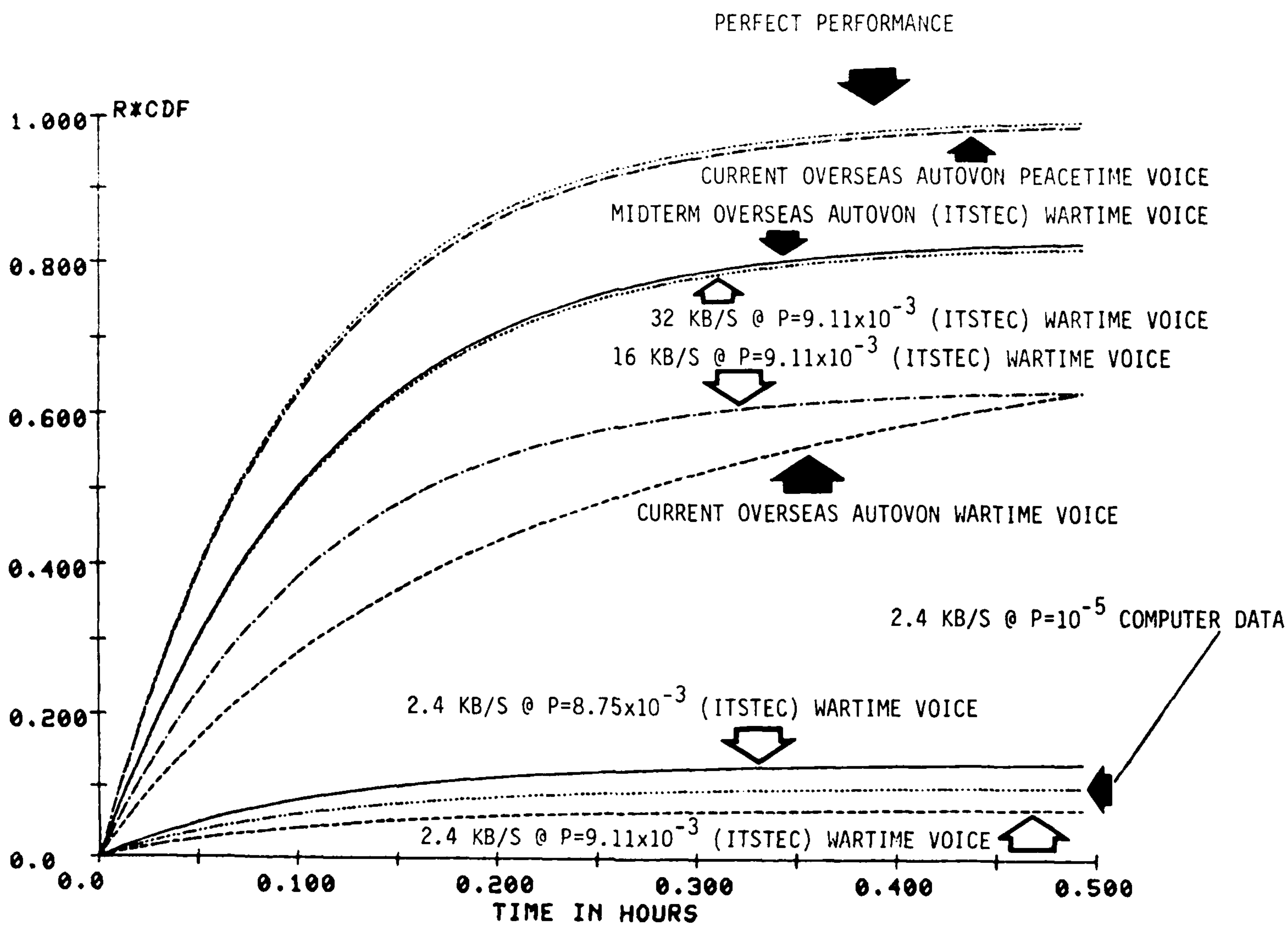

Figure 1. Effectiveness, No Dynamic Repair

Assume an MTTR = 1/ML of 0.5 hour, counting only reported outages $>$ 1/60 hour. Further, assume AL = .99 produces FL = 0.0202/hour. Consider next the short term failure rate parameter FS. By definition, a short term failure occurs when, given the previous interval was acceptable, the number of error bits observed over a short (i.e., $\leq$ 1 minute) interval t equals or exceeds an unacceptable threshhold. Let PU be the unacceptable error probability and let P be an error probability as averaged over 1 minute intervals while the path is in use.

We further assume, for this initial model, a purely random channel in which the number of error bits arriving in any interval t is Poisson distributed [18]. The probability of no short term failures over interval t, i.e., exp(-FSt), is also the Poisson CDF.

$$\sum_{j=0}^{(PU)Bt-1} \exp(-PBt)(PBt)^j/j! \tag{4}$$

where B is the bit rate, PU is the unacceptable error probability threshhold, and (PU)Bt-1 is the maximum number of error bits allowed in interval t if a no failure event occurs. For the voice mode, we assume PU = 10^{-2}, and t = 5 seconds, hence, (PU)Bt-1 = 119 error bits at 2.4 kb/s or 799 error bits at 16 kb/s.

The Poisson cumulative distribution function is tabulated in reference [19] as a Chi squared distribution with V degrees of freedom, $Q(X^2/V)$, where X^2 corresponds to 2PBt and V corresponds to 2(PU)Bt in our problem. For V $>$ 100, $Q(X^2/V)$ (which we associated with the probability of acceptable reception) is approximately equal to Q(X1) = 1-P(X1), with

$$X1 = 2(PBt)^{1/2} - (4(PU)Bt-1)^{1/2} \tag{5}$$

where P(X1) (the short term probability of unacceptable reception) is the cumulative distribution function of the normal distribution with mean 0, variance 1. Using the normal approximation, P = 10^{-5}, and the aforementioned parameter values, we find P(X1) is $10^{-99.29}$ at B = 2.4 kb/s, and $10^{-658.96}$ at B = 16 kb/s. The conditional probability that the path does not fail over short interval t, i.e., exp(-FSt), is the same as the short term probability of acceptable reception, 1-P(X1). Hence, FS = -(1/5) Ln (1-P(X1)). Since -Ln(1-P(X1)) is nearly equal to P(X1) for P(X1) $\ll$ 1, FS (per 5 seconds) is about P(X1)/5 sec; hence the failure rate per hour values of FS are 720 P(X1), or 3.7×10^{-97} at 2.4 kb/s and 7.9×10^{-657} at 16 kb/s.

To compute MS, the conditional mean short term repair rate, first consider the compound event: acceptable at time 0, unacceptable for the next j intervals (duration jt), acceptable over interval (j+1). Using P(X1) = probability of being unacceptable over interval t, then the compound event has a joint probability $(1-P(X1))\, P(X1)^j\, (1-P(X1))$. Dividing this joint probability by the joint probability of being acceptable at time 0 and acceptable over interval j+1, produces the conditional probability of being unacceptable (i.e., undergoing "repair") for a continuous duration jt as $P(X1)^j$. Hence, $P(X1)^j = \exp(-MSjt) = \exp(-MSt)^j$ and MS can be computed for the voice case under discussion, as $MS = -(1/5)\ Ln\ (P(X1))$. Results using t=5 seconds and $P=10^{-5}$ are $MS = 1.65 \times 10^5$/hour at 2.4 kb/s and 1.092×10^6/hour at 16 kb/s.

Since $MS = -(1/t)\ Ln\ (P(X1))$ implies $P(X1) = e^{-MSt}$ and $FS = -(1/5)\ Ln\ (1-P(X1))$ implies $(1-P(X1)) = e^{-FSt}$, then $e^{-MSt} + e^{-FSt} = 1$, which says that over interval t the probability that the channel is in a failed or non-failed state is 1.

$AS = 1/(FS/MS + 1)$ is nearly 1 for B > or = 2.4 kb/s when we use the previously derived values of FS and MS at $p = 10^{-5}$.

The curve in Figure 1, labeled current overseas AUTOVON, peacetime environment, voice ($P = 10^{-5}$ at 2.4 kb/s) was plotted using the parameters just derived, i.e., AL = .99, ML = 2/hour, FL = .0202/hour, $FS = 7.2 \times 10^{-97}$, $MS = 1.64 \times 10^5$/hour, AS =1. The $Pr[d \leqq D] \times R$ is close to ideal performance. The next curve, labeled current overseas AUTOVON, wartime environment, uses FL = 2.0202, ML = 2/hour, AL = .4975, and the same short term parameters. The next curve, labeled mid-term overseas DSN, wartime environment, uses the same assumed wartime FL (and the same short term parameters) but the long term mean time to restore/repair has been reduced from 30 to 3 minutes, producing ML = 20/hour, AL = .908. This last curve is intended to show the endurability enhancement of a faster acting tech control such as ITSTEC.

Next, noting that the 1 minute error probability P could increase substantially, particularly where tactical circuits might be part of the path, Table I shows how FS and MS vary with P at B = 2.4, 16 and also 32 kb/s.

TABLE I

VARIATION OF SHORT TERM VOICE MEAN FAILURE RATES (FS)
AND REPAIR RATES (MS) WITH ERROR PROBABILITY (P) AND BIT RATE (B)

P	B = 2.4 kb/s		B = 16 kb/s		B = 32 kb/s	
	FS in $hours^{-1}$	MS in $hours^{-1}$	FS in $hours^{-1}$	MS in $hours^{-1}$	FS in $hours^{-1}$	MS in $hours^{-1}$
10^{-5}	$3.69x10^{-97}$	$1.65x10^{5}$	$7.89x10^{-657}$	$1.09x10^{6}$	10^{-1306}	$2.17x10^{6}$
10^{-4}	$7.7x10^{-84}$	$1.43x10^{5}$	$2.44x10^{-564}$	$9.39x10^{5}$	10^{-1128}	$1.88x10^{6}$
10^{-3}	$5.2x10^{-48}$	$8.31x10^{4}$	$1.28x10^{-324}$	$5.42x10^{5}$	10^{-654}	$1.09x10^{6}$
10^{-2}	512.3	486.1	504.2	494.0	495.5	502.7

A large increase in FS occurs somewhere between $P=10^{-2}$ and 10^{-3} at all of the bit rates, i.e., a threshhold effect is evident. Recalling that averaged over T, R = M/(M+FL+FS), one can define an onset of the threshhold effect, by setting FL = 0 and choosing that value of FS which produces M/(M+FL+FS) = 0.99. Using M = 10/hour, FS at threshhold = 0.101010, and since FS = -720 lnQ(X1), Q(X1) is .999859718, where X1 is about -3.632679. Using this X1 value in equation (5) with PU = 10^{-2}, T = 5 seconds, and choosing a bit rate B gives a value of P corresponding to FS at the onset of threshhold. The threshhold values of P are: 9.11 x 10^{-3} at 32 kb/s; 8.75 x 10^{-3} at 16 kb/s; and 6.94 x 10^{-3} at 2.4 kb/s. One can get a feeling for relative robustness of the various bit rates, by plotting P ($d \leq D$) x R for each bit rate as P degrades from 10^{-5} to 6.94 x 10^{-3} to 8.75 x 10^{-3} to 9.11 x 10^{-3}. Some of these curves are shown in Figure 1, as indicated, and also include the effects of the previously assumed wartime long term failure rate FL = 2.0202/hour and ITSTEC long term repair rate = 20/hour.

Just above the lowest curve is one labeled computer data 2.4 kb/s at P = 10^{-5}. Parameters used were Fs = BP = 86.4/hour and MS = -BLn(1-exp(-P)) = 9.947 x 10^7/hour. These parameters were derived using a 1 bit measurement interval in equation (4), hence t = 1/B, using an unacceptable error probability threshold of 1 bit in error. Note that 1/Fs = 1/BP is the mean error free interval.

The performance curves of Figure 1 for digital voice confirm the decisions of TRI-TAC to operate at higher bit rates such as 32 or 16 kb/s, from the standpoint of relative robustness as average error rate degrades. For similar, i.e., quality reasons, the WWSVA study recommended retention of a higher quality 16 kb/s rate. The performance curve for computer data reflects the need for more reliable network transmission, which has led to development and operation of a separate network for data, as exemplified by AUTODIN I and the forthcoming AUTODIN II. The key feature of such data networks from our model viewpoint is the ability to dynamically restore the information which has failed. One also notes (from Figure 1) that although ITSTEC with its higher assumed mean restoral rate (ML = 20/hr) was a decided improvement over the current system (ML = 2/hour), effectiveness will be severely limited by the short term reliability.

Therefore, in our search for more endurable systems, we next consider the performance of systems which can dynamically repair during the information transfer interval.

In the section which follows, we will show that for systems employing dynamic repair, the joint probability that the information transfer is completed within a delay < or = D, and that the path stays reliable over the information transfer duration, approaches 1 as delay D approaches infinity. In the circuit switched case previously considered, the corresponding probability that the path stayed reliable as averaged over the assumed distribution of information transfer lengths was M/(M+FS+FL). It is only fair to point out that in the circuit switched case, we have implicitly assumed impatient subscribers who give up in the event of an information transfer failure. Conversely, if one assumed patient subscribers, who are willing to keep repeating their information transfer attempts whenever failures have occurred, they too would ultimately get through.

Derivation of the case which is comparable to the circuit switched case considered, i.e., both short and long term reliability and a 1 minute delay before repairs begin, requires conversion to Z transforms before transform inversion and is not presented in this paper. However, we present two mathematically simpler cases where closed form analytical solutions can be readily obtained.

First, we consider the case of constant information transfer duration T. A successful event occurs when the path is available, or if not available it is repaired and the duration is T and the path is reliable (over duration T); or if not reliable the path is repaired and stays reliable; or if it doesn't stay reliable, it is repaired and stays reliable; or if . . . and so on ad infinitum. Symbolically, this event can be represented as

$$(a+\bar{a}\ re)T(r+\bar{r}\ re(r+\bar{r}\ re(r+\bar{r}\ re(\ .\ .\ .\ )$$

which equals

$$= (a+\bar{a}\ re)T\ (1+\bar{r}\ re + (\bar{r}\ re)^2 + (r\ \bar{r}e)^3 + \ .\ .\ .)\ r$$

$$= (a+\bar{a}\ re)Tr/(1-\bar{r}\ re)$$

where, as before, a and $\bar{a}$ are, respectively, the events that the path is available and not available, re is the event that the path is repaired/restored *given it was in a failure mode, and r and* $\bar{r}$ *are the* respective events that the path stays reliable and not reliable over interval T. The probability that the delay to completion is exactly t seconds and the information transfer stays reliable over T seconds will be, assuming independence,

$$AR(P(T) + \bar{R}\ P(T)*Re + \bar{R}^2P(T)*Re*Re + \bar{R}^3P(T)*Re*Re*Re + \ .\ .\ .)$$

$$+(1-A)R(Re*P(T) + \bar{R}\ Re*P(T)*Re + \bar{R}^2\ Re*P(T)*Re*Re + \ .\ .\ .)$$

where the * is the convolution process involving only those probability elements introducing time delay. To be consistent with previous notation, let AS = P(a), $\overline{AS}$ = 1-AS = P($\bar{a}$), P(T) = δ(t-T), where δ(t-T) = 1 if t = T, δ(t-T) = 0 if t = T, and Re = P(re) = MSe^{-MSt} is the probability that the path is repaired/restored in exactly t seconds. Finally, RS = P(r) and (1-RS) = P($\bar{r}$).

Following the basic theory discussed in reference [20], if one Laplace transforms only those probability elements which contribute (additively) to the time delay, i.e., those which are convolved, the product of the Laplace transforms when inverse transformed will produce the probability density function of the sum of the time delays. Furthermore, to obtain the joint probability that the total delay < or = D and that the path stays reliable over interval T, one need only multiply the product of the Laplace transform of the probability density function and reliability by 1/s and then invert the Laplace transform. For multiplication of a Laplace transform by 1/s, and inversion will produce the integral from 0 to t=D of the original function. We now carry out the process step by step, first deriving the joint probability that the delay = t and that it stays reliable over duration T, and then deriving the product of the cumulative distribution function and R(T). Using $L[P(T)] = L[\delta(t-T)] = \exp(-sT)$ and $L[Re] = L[MS\exp[-MSt]] = MS/(MS+s)$ in the closed form event probability equation

$$[P(a) + P(\bar{a})P(re)]\ P(T)\ P(r)/[1-P(r)P(re)]$$

$$= [AS + (1-AS)Re]\ P(T)\ R/[1-(1-R)Re]$$

produces

$$L[Pr[delay=t]] \times R = [AS + (1-AS)MS/(MS+s)]\ \exp(-sT)R/[1-(1-R)MS/(MS+s)]$$

which after simplification produces:

$$L[Pr[delay=t]] \times R = [(ASs+MS)/(s+MSR)]\ [\exp(-sT)]R.$$

Writing the term ASs/(s+MSR) as AS - AS MSR/(s+MSR) produces

$$L[Pr[delay=t]] \times R = [AS + MS(1-ASR)/(s+MSR)]\ [\exp(-sT)]R.$$

Inverting the above transform produces

$$Pr[delay=t] \times R = ASR\,\delta(t-T) + MSR(1-ASR)\ \exp[-MSR(t-T)]\ U(t-T).$$

One also notes for future use that

$$L[Pr[delay=t]] \times R = ASR\ \exp(-sT)\ [1+ MS(1-ASR)/(AS(s+MSR))] \quad (6)$$

$$L[Pr[delay \le t]] \times R = (1/s)\ ASR\ \exp(-sT)\ [1+MS(1-ASR)/(AS(s+MSR))]$$

which after inversion produces the result of interest:

$$Pr[delay \le t] \times R = U(t-T)\ [1- (1-AS\ R)\ \exp(-MSR(t-T))]. \quad (7)$$

Observe that as $t \to \infty$, Pr [delay < or = ∞] x R = limit as $t \to \infty$ of U(t-T); *i.e., the information is ultimately reliably transferred with* probability = 1. Also, using R = exp(-FST) where FS is the average short term failure rate, and recalling that AS = 1/(1+FS/MS) and at FS=0, AS=1, R=1, results in Pr[delay < or = t] x R = U(t-T). In other words, perfect performance is achieved at AS=1, R=1, the only delay being that due to the message interval T.

For purposes of comparison, a system without dynamic repair during the information transfer interval would have

$$L[\Pr[\text{delay} < \text{or} = t]] \times RS = (1/s)[AS + (1-AS)MS/(s+MS)] \exp(-sT)RS$$

which upon inversion yields

$$\Pr[\text{delay} < \text{or} = t] \times RS = U(t-T)\ [1-(1-AS)\ \exp[-MS(t-T)]]RS. \tag{8}$$

Equation (8) also produces $\Pr[\text{delay} < \text{or} = t] \times RS = U(t-T)$ at $AS=1$, $RS=1$, as did Equation (7). However, as t approaches ∞, $\Pr[\text{delay} < \text{or} = t] \times RS$ approaches RS for equation (8).

Using equation (7), one can express the time behavior of the dynamic repair case as

$$t-T = -(1/MS\ RS)\ln[(1-\Pr[\text{delay} < \text{or} = t]\ RS)/(1-AS\ RS)] \tag{9}$$

where $t >$ or $= T$ and $1-\Pr\ [\text{delay} < \text{or} = t] \times RS$ or $= 1-AS\ RS$.

It will be easier to study the tradeoffs on t-T if we express AS, RS and MS, which are not independent, in a more fundamental way. Recall, from equation (4) and subsequent developments, that

$$\sum_{j=0}^{(PU)Bt^*-1} \exp(-PBt^*)\ (PBt^*)^j/j! = e^{-FSt^*} = Q(X^2/V) \tag{10a}$$

$$RS = e^{-FST} = e^{-FSt^*(T/t^*)} = [Q(X^2/V)]^{-T/t^*} \tag{10b}$$

$$e^{-MSt^*} + e^{-FSt^*} = 1 \tag{10c}$$

$$MS = -1/t^*\ \ln[P(X^2/V)] \tag{10d}$$

$$AS = 1/(FS/MS + 1) \tag{10e}$$

$$Q(X^2/V) = 1-P(X^2/V) \tag{10f}$$

$$X^2 = 2P\ Bt^* \tag{10g}$$

$$V = 2(PU)\ Bt^* \tag{10h}$$

where $P(X^2/V)$ is the cumulative distribution function of a chi squared distribution with V degrees of freedom. Using these relationships, equation (9) can be expressed as

$$(t-T) = [t^*/(Q(X^2/V))^{T/t^*}\ln(P(X^2/V))] \times$$

$$\ln \left[\frac{(1-\Pr(\text{delay} < \text{ or } =t) \times RS)(\ln[Q(X^2/V)\ P(X^2/V]}{\ln[Q(X^2/V)] + [1-(Q(X^2/V))^{T/t^*}] \times \ln[P(X^2/V)]} \right] \quad (11)$$

By similar substitutions, one can also rewrite equation (8) as

$$\Pr[\text{delay} < \text{ or } =t] \times RS = U(t-T) \left\{ 1-[\ln Q(X^2/V)/\ln(Q(X^2/V)P(X^2/V))] \times \exp[(t-T)(\ln[P(X^2/V)])/t^*] \right\} Q(X^2/V)^{T/t^*}. \quad (12)$$

Using equations (11) and (12) and relating $P(X^2/V)$ and $Q(X^2/V)$ to the measurement interval t^* and error probability P, Tables II and III were constructed to show how performance varies as a function of P, t^* and system category (dynamic repair using repeat vs no dynamic repair).

Table II, the data case, uses a constant information transfer duration of T=360 seconds; 1 bit or more in error over the measurement interval is unacceptable, i.e., $(PU)Bt^* - 1 = 0$, B=2400 b/s, and $t^* = 1/B$ as well as $t^* = 1$ second. Performance for the dynamic repair case using repeat is shown in terms of the value of t-T from equation (11), i.e., the delay minus the constant message interval T due to path outages and "repairs", at a "probability of success" = .99. Here, "probability of success" is Probability (delay < or =t) x RS(T). For comparison, the corresponding "probability of success" for the non-dynamic repair case is also shown as derived from equation (12).

TABLE II

DATA PERFORMANCE AS A FUNCTION OF ERROR PROBABILITY P

Parameters: T = 6 minute message duration; Bit rate B = 2400 b/s; Measurement interval t^* = 1/2400 sec (1 bit) or 0.8333 sec (2000 bits).

PS, probability of success, is probability [(delay to completed transfer -T) ≤ or = delay, t] x R(T). Here R(T) is the reliability, or probability the path does not fail over message interval T.

P	t^* (secs)	DELAY, t (secs) at PS = .99, Dynamic Repair via Feedback	PS No Dynamic Repair
10^{-3}	1/2400	4.7×10^{371}	6×10^{-376}
10^{-4}		6.9×10^{33}	3×10^{-38}
$10^{-4.8}$		153.7	1×10^{-6}
$10^{-4.9}$		9.0	1.9×10^{-5}
10^{-5}		.94	1.8×10^{-4}
10^{-6}		2.9×10^{-4}	.42
10^{-3}	.8333	4.5×10^{376}	6×10^{-376}
10^{-4}		7.5×10^{37}	3×10^{-38}
10^{-5}		5531.5	1.8×10^{-4}
$10^{-5.1}$		884.0	1×10^{-3}
$10^{-5.2}$		204.1	4.3×10^{-3}
$10^{-5.3}$		63.1	1.3×10^{-2}
$10^{-5.4}$		24.6	3.2×10^{-2}
$10^{-5.5}$		11.5	6.5×10^{-2}
$10^{-5.6}$		6.2	.11
$10^{-5.7}$		3.7	.18
$10^{-5.8}$		2.5	.25
$10^{-5.9}$		1.7	.34
10^{-6}		1.3	.42
10^{-7}		.23	.92

For the case of dynamic repair via repeat, the delay increases sharply with increasing path error probability. A shorter measurement interval appears to be less robust in that for a given decrease in error probability the increase in delay becomes greater. However, shortening the measurement interval, t^*, at a given error probability shortens the delay. For example, Table II shows at $P=10^{-5}$, and $Bt^* = 1$ bit ($t^* = 1/2400$ seconds), a .94 second delay, while at $Bt^* = 2000$ bits ($t^* = .8333$ seconds) the corresponding delay is 5531.5 seconds. This effect is primarily due to changing the average path repair rate, MS. For, recall that for the data case, 1 bit in error per measurement interval results in an interval reliability $RS = Q(X^2/V)^{T/t^*} = \exp(-PBt)$, which is independent of t^*. However, $MS = -1/t^* \ln(P(X^2/V)) = -1/t^* \ln(1 - \exp(-PBt^*))$; thus decreasing t^* increases MS, thereby shortening the delay. Increasing the bit rate while holding the number of bits per measurement interval constant is another way of shortening the measurement interval.

For the data case without dynamic repair, the right hand side of equation (8) approximately equals $U(t-T)RS$, where $RS = \exp(-PBT)$. As such, for T=360 seconds, B=2400 b/s, $P=1.16 \times 10^{-8}$ is required for PS=.99.

Next, the voice case is considered. The delay and accuracy requirements for voice differ from those of data. Voice telecommunications should emulate natural conversation. This requires very short total delays, of the order of a small fraction of a second, to avoid the adverse psychological effects of long delays in replies. Conversely, data telecommunications do not have such real time requirements. Accuracy requirements for voice are much less stringent than for data; e.g., relative threshholds of acceptable error rates are of the order of 10^{-2} for voice vs 10^{-9} to 10^{-10} for computer data.

Table III essentially shows, for the case of dynamic repair using repeat and assuming a 6 minute call duration, how the delay at a prespecified accuracy level varies, as the error probability P averaged over the indicated measurement interval t^* changes. Additionally, it shows an associated measure of accuracy performance for the case without dynamic repair at $t^* = 5$ seconds, and the average number of "failures" per call duration at both $t^* = 5$ and $t^* = 1$ second. A failure is defined to occur when the P averaged over t^* equals or exceeds 10^{-2}. The tabulated values were derived using equations (10), (11), and (12).

TABLE III

VOICE PERFORMANCE AS A FUNCTION OF ERROR PROBABILITY P

Parameters: T = 6 minute call duration; Bit rate B=2400 b/s; Measurement interval $t^* = 5$ seconds or $t^* = 1$ second.

PS, probability of success, is probability [(delay to completed transfer -T) < or = delay, t] x R(T). Here R(T) is the reliability, or probability the path does not fail over call interval T.

P	$t^* = 5$ secs			$t^* = 1$ sec	
	Delay, t (secs) at PS = .95, Dynamic Repair via Repeat	PS, No Dynamic Repair	Av. Failures /Call Interval	Av. Failures /Call Interval	Delay, t (secs) at PS = .95, Dynamic Repair via Repeat
10^{-2}	3.9×10^{23}	5.6×10^{-23}	51.2	259.6	5.9×10^{117}
$10^{-2.1}$	4.7	5.6×10^{-23}	.66	60.5	2.9×10^{26}
$10^{-2.13}$	.4	.91	.09	34.8	1.7×10^{15}
$10^{-2.135}$	.15	.939	.063	31.6	6.5×10^{13}
$10^{-2.136}$	.08	.943	.058	31.	3.5×10^{13}
$10^{-2.137}$	.04	.947	.054	30.4	1.9×10^{13}
$10^{-2.13775}$	0	.95	.05	30.	1.2×10^{13}
$10^{-2.3}$	0	$1-6.6 \times 10^{-9}$	6.6×10^{-9}	.55	.57
$10^{-2.375}$	0	1.	0.	.05	5×10^{-4}

Choice of a 5 second measurement interval provides a point of reference for voice, based upon the criterion a call fails only when the error probability P equals or exceeds 10^{-2} over a 5 second interval. As such, the failure rate is no higher than it need be for voice. However, the time to detect a failure (5 seconds) far exceeds the short delay requirement for voice. In effect, the useful range of P values is essentially the same for both the dynamic repair with repeat and no dynamic repair cases.

The 1 second measurement interval was chosen because it is close to the packet interval for AUTODIN II data at 2400 b/s. The relative delay performance of dynamic repair using repeat becomes even worse because shortening the measurement interval increases the number of failures per call. Note that using equations (10a), (10g) and (10h), the failure rate per call of interval T, $FS \times T = -(T/t^*) \ln[Q(X^2/V)]$ with $X^2 = 2\ PBt^*$ and $V=2(PU)Bt^*$ increases for this case where the number of bit errors per measurement interval, $(PU)Bt^*-1$, exceeds zero. By contrast, recall that in the data case, $(PU)Bt^* = 1$, zero bit errors were allowed, and FS is independent of t^*.

One major problem encountered thus far in using dynamic repair with repeat for voice is the delay caused by the long measurement interval. As a logical next step, we investigate the dynamic repair with repeat case where the measurement interval, say 100 bits at 2400 b/s, is very short. We also investigate the behavior of the measure of effectiveness for the repeat case when the information transfer is broken into n shorter packets. This requires a generalization of equation (7), which represents the case for n=1.

In Appendix A, we derive the following expression for an n packet information transfer of duration $T=nt^*$, under the assumption of independence from packet to packet.

$$\Pr[\text{delay} - T \le t] \times RS(nt^*) = (ASRS)^n + \sum_{j=1}^{n} \binom{n}{j} (ASRS)^{n-j}(1-ASRS)^j \left(1-\sum_{k=0}^{j-1} e^{-MSRSt} (MSRSt)^k/k!\right) \qquad (13)$$

In equation (13), AS, RS, and MS are, respectively, the short term availability, reliability, and average repair rate as measured over the packet interval t^*. The expression $\binom{n}{j} = (n!/((n-j)!j!)$ is the number of combinations of n packets taken j at a time, and represents the number of mutually exclusive ways in which n-j packets are available and reliable, and j packets are not available and reliable. The term

$$\left(1 - \sum_{k=0}^{j-1} e^{-MSRSt} (MSRSt)^k/k!\right)$$

is interpreted as the probability that j or greater events occur in interval t. These events, mean rate MSRS, consist of repair of the failed path and, given the path is repaired, it stays reliable over the packet duration. One also notes that $(1 - \sum_{k=0}^{j-1} e^{-MSRSt}(MSRSt)^k/k!)$ is the cumulative distribution function of a chi squared distribution, $P(X^2/V)$ with X^2 = 2MSRSt, and V = 2j degrees of freedom. For n=1, equation (13) reduces to equation (7) (with T=0).

In numerically evaluating equation (13), we have been limited to a maximum of n=256 packets because $\binom{n}{j} = 0.5788 \times 10^{76}$ at n=256, j=128 is just about at the maximum of 0.7327×10^{76} allowed by the IBM 370 employed in the calculation.

Figure 2 shows curves of equation (13) for a constant message length of 25,600 bits at an error rate $P=10^{-4}$, as one successively quadruples the number of packets per message, up to a maximum of n=256 packets. We have uniformly applied the criterion that a packet is reliable if it has zero bits in error. The improvement in response time for data with increasing the number of packets per message, or equivalently shortening the packet length, is striking.

Although not shown in Figure 2, the corresponding graph for voice without dynamic repair at $P=10^{-4}$, B=2400 b/s and T=(25600/2400)s can be computed using an appropriate transformation of equation (8) as

$$Pr[delay - T \leq t] \times RS(T) = U(t)\ [1-(1-AS)e^{-MSt}]e^{-FST}.$$

Using the corresponding values of MS, FS From Table I, results in

$$Pr[delay - T \leq t] \times RS(T) = U(t)\ [1-1.76 \times 10^{-84}),$$

which is very close to ideal performance (value U(t)) and for practical purposes is still better than employing dynamic repair.

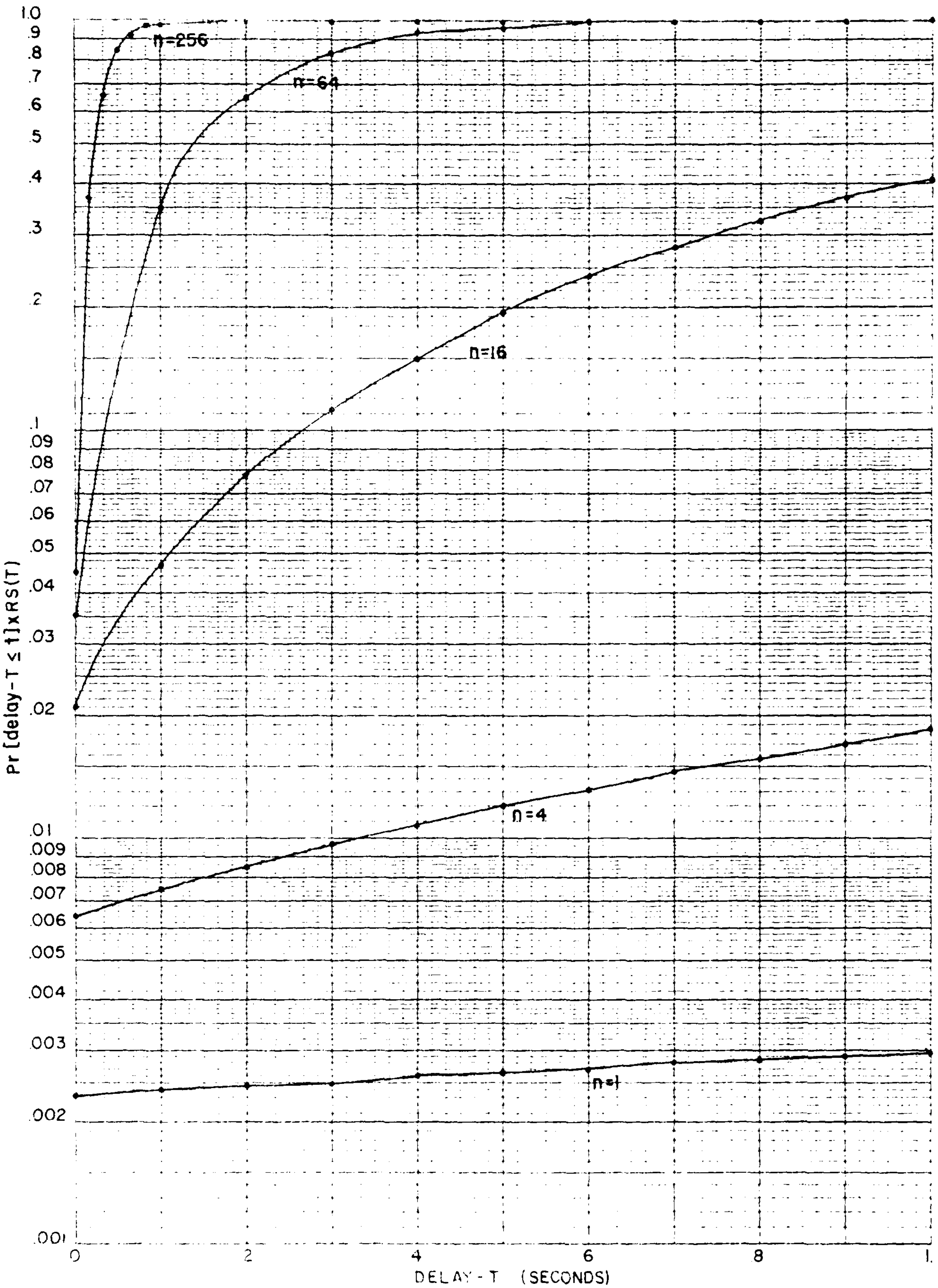

FIGURE 2. EFFECTIVENESS, n PACKETS, eq.(13)

IV. SIGNIFICANT FINDINGS AND CONCLUSIONS

A measure of effectiveness (M.O.E.) was formulated in terms of the product of the probability (delay $\leq$ t) x probability (the information is reliably transferred over its interval) given an environment/stress level. Partitioning into long and short term parameters allowed accounting for quality/accuracy effects in terms of short term parameters, using a Poisson model, which were related to average error probability, bit rate, unacceptable error probability threshold and measurement interval.

The M.O.E. was evaluated, omitting queueing delays, for two basic cases: (1) no dynamic repairs (during the information transfer interval), and (2) dynamic repair via repeat. For the no dynamic repair case, with an exponentially distributed information transfer interval of average duration 1/M, the reliability (part of the M.O.E.) is asymptotic to M/(M+FL+FS) where FL and FS are the mean long and short term failure rates. Such reliability effects are illustrated, by the relative robustness of higher bit rates for voice and by poor data performance. ITSTEC is shown to be a substantial improvement, but will still be severely limited by short term failure rates. In the dynamic repair via repeat case, the M.O.E. was derived for a constant information transfer duration with short failures and repairs. As the delay approaches infinity, Pr[delay $\leq$ t] x R approaches 1 with dynamic repair, and R without it. Performance variation as a function of error probability and measurement interval is studied for data and voice, at 2.4 kb/s based on a random channel model. Dynamic repair via repeat functions well for data, but delays inhibit its utility for voice.

Finally, assuming short term poisson failures and exponentially distributed repair times, and an n packet message, an expression for the M.O.E. (Pr[delay $\leq$ t] x R) is derived and physically interpreted. Response time improvements of packetizing data are shown.

In view of the poor reliability of no dynamic repair, and the intolerable delay of dynamic repair via repeat for voice, dynamic repair via fast switching deserves study and consideration.

REFERENCES

[1] A. Babbitt, "New Communications and Technology in WWMCCS," SIGNAL, August 1977.

[2] I. Lebow, "The Impact of Technology on the Future DCS," SIGNAL, August 1977.

[3] WSEO, "WWMCCS Current System Description 1978 (U)," Volume V (SECRET).

[4] DCA, "World Wide Secure Voice Architecture Final Report (U)," Code 900, Jan 1979 (SECRET).

[5] DCA Report, "Qualitative Requirements for the World Wide Digital Systems Architecture (WWDSA) (U)," Code 900, July 1980 (SECRET).

[6] DCA Report, "Initial Baseline Description for the World Wide Digital Systems Architecture (WWDSA) (U)," Code 900, Aug 1980 (SECRET).

[7] DCA Report (Draft), "Significant Issues for the World Wide Digital Systems Architecture (WWDSA) (U)," Code 900, Aug 1980 (SECRET).

[8] DCEC TR 18-78, "Design Concepts for the Next Generation CONUS AUTOVON (U)," Dec 1978.

[9] DCEC Report (Draft), "Concept Plan for the DSN," Code R500, 1979.

[10] DCEC Report (Draft), "A Concept and Plan for Integrated Transmission, Switching and Tech Controls In the Overseas Intra-Theater DCS," T.M. Shimabukuro, Code R700, 30 July 1979.

[11] R.E. Lyons, "DoD Data and Integrated Communications: Present Programs and Future Plans," a presentation to the DCA Scientific Advisory Group, 10 Jan 1980.

[12] DCA Report (Draft), "Synthesis of Switching Functions for Future Defense Communications Systems," G.J. Coviello and R.E. Lyons, Dec 1979.

[13] M.I.T., Lincoln Laboratory W-Note-5 (Draft), "Experiment Plan for the Wideband Integrated Network - Supplement I," Mar 1980.

[14] MILSATCOM Systems Office, TR 79-3, "Expanded Frame Work for MILSATCOM Development (U)," Sep 1979 (SECRET).

[15] DCEC SATCOM Systems Engineering Branch Memorandum, "Objectives, Requirements, and Constraints of the DSCS II Space Segment (U)," 6 Mar 1975 (SECRET).

[16] Computer Sciences Corporation, "The Profile of a Selected DSCS Wideband User (U)," Feb 1980 (SECRET).

[17] H. Yakabe, "Formulation of the Follow-On Defense Satellite Communications System Concept (U)," 1975 IEEE Intercon Conference Record (Apr 1975), pp. 29/4/1-4.

[18] Canada, Bell-Northern Research, "Considerations on the Relationship Between Mean Bit Error Ratio, Averaging Periods, Percentage of Time and Percent Error Free Seconds," CCITT Study Group XVIII, Contribution No. 343, October 1979.

[19] M. Abramowitz and I. Stegun (Eds.), Handbook of Mathematical Functions, Dover Publications, Inc., New York, (1970), pp. 941, 978.

[20] G. Whitehouse, Systems Analysis and Design Using Network Techniques, Prentice Hall (1973), pp. 242-301.

Glossary of Terms

a	event that the path is available (in a nonfailed state) at the instant of demand t.
$\overline{a}$	event that the path is not available (in a failed state) at the instant of demand t (complement of a).
aL	event that the path is long term available at the instant of demand t; i.e., counting only failures > 1 minute duration, it is in a non-failed state.
$\overline{aL}$	event that the path is not long term available; i.e., counting only failures > 1 minute duration, it is in a failed state.
aS	event that the path is short term available, counting only failures where the measurement interval is < or = 1 minute duration at the instant of demand t given event aL.
$\overline{aS}$	event that the path is not short term available at the instant of demand given event aL, counting only failures involving a measurement interval < or = 1 minute.
AL	long term availability, the probability of event aL, estimated a 1 - (sum total of outages > 1 minute duration divided by the total measurement interval). AL = ML/(ML+FL).
ARQ	Automatic Repeat Request.
AS	short term availability: the probability of event aS, estimated as 1- (sum total of outages involving < or = 1 minute measurement durations divided by a total measurement interval which excludes outages whose duration are < 1 minute). AS = MS/(MS+FS).
B	bit rate, in bits/time.
CDF	Cumulative Distribution Function: the probability that a random variable is < or = some specified value.
d	time delay, used as a random variable.
D	time delay, used as a specified value.
E_i	Environment/stress level i.

F	Conditional average path failure rate, given the path was available at the start of any measurement interval. Estimated as 1/MTTF. F = FL+FS.
FL	Conditional average path long term failure rate, given the path was long term available at the start of any such event and counting as failures only those outages > 1 minute. Estimated as the reciprocal of the mean conditional time to a long term failure.
FS	Conditional average short term failure rate, given the path was long term available at the start of any such event and counting as failures only outages involving measurement intervals < or = 1 minute.
i.t.	information transfer
ITSTEC	Integrated Switching and Tech Control
ln	natural logarithm
L	long (> 1 minute)
M	average rate of i.t. duration, or 1/average message length.
ML	average rate of long term path restoral, i.e., reciprocal of the average time to repair/restore, including only outages > 1 minute.
M.O.E.	Measure of Effectiveness
MS	Conditional average rate of short term path restoral, given event aL, i.e., reciprocal of the average time to repair/restore, including only restoral times associated with measurement intervals < or = 1 minute.
MTTF	Mean time to failure, measured from a time when the path was in a non-failed state.
MTTR	Mean time to repair/restore, measured from the time of path failure.
n	number of packets.
P	probability of a bit error
pdf	probability density function
Pr	probability
PU	Unacceptable bit error probability threshold, e.g., 10^{-2} for voice.

P(X1)	Cumulative distribution function (CDF) of the normal distribution, mean 0, variance 1, at specified value X1. As used in this report it is also the short term probability of unacceptable reception.
Q(X1)	1-P(X1)
$Q(X^2/V)$	1- cumulative distribution function (CDF) of a chi-squared distribution function with V degrees of freedom.
r	Conditional event of the path stays reliable (does not fail) over a specified interval, given it was available at the start of the interval.
$\overline{r}$	Conditional event that the path does not stay reliable (does fail) over a specified interval, given it was available at the start of the interval.
re	Conditional event that the path is repaired/restored, given it was in a failed state.
reL	Conditional event that the path is repaired/restored, given it was in a failed state lasting $>$1 minute.
reS	Conditional event that the path is repaired/restored, given it was in a failed state lasting $<$ or = 1 minute.
rL	Conditional event that the path stays long term reliable (does not fail, including only outages $>$ 1 minute) over a specified interval, given it was long term available at the start of the interval.
rS	Conditional event that the path stays short term reliable (does not fail, counting only failures with measurement intervals $<$ or = 1 minute duration) over a specified interval, given it was available at the start of the interval.
R	Reliability, the probability of conditional event r.
$\overline{R}$	1-R
s	Laplace transform variable.
S	short term, i.e., $<$ or = 1 minute.
t	time
T	duration of information transfer interval.
U(t)	Unit step function, value 0 for $t<0$, 1 for $t\geq 0$.
W	Waiting time due to queueing.
$\delta(t)$	Unit impulse function, value 0 for $t\neq 0$, 1 for $t=0$.

APPENDIX A

DERIVATION OF THE CDF OF DELAY X RS FOR AN N PACKET CASE

From equation (6) in the main body of the report, the Laplace transform (of probability density function of delay due to repairs) x the reliability over a packet interval t^* is

$$L[PR[delay=t]xRS(t^*) = AS\ RS(t^*)\ [1+(1-AS\ RS(t^*)MS/(AS(s+MSRS(t^*))](A1)$$

for an information transfer interval $T=nt^*$ consisting of n packets. If the probabilities are independent from packet to packet, the corresponding result is, using $RS(t^*)^n = RS(nt^*)$. Equation (A2) uses the fact that

$$L[Pr[delay=t]x\ RS(nt^*) = [AS\ RS(t^*)]^n\ [1+(1-AS\ RS(t^*)) \quad MS/(AS(s+MS\ RS(t^*))]^n \qquad (A2)$$

since the density function of the sum of n independent, identically distributed delays is their n fold convolution in the time domain, or equivalently their n fold product in the Laplace transform domain. Expanding (A2) via the Binomial theorem, and for simplicity of notation, using AS=A, $RS(t^*)$=R, MS=M, and 1-ASRS=AR produces

$$L[Pr[delay=t]xR(nt^*)=(AR)^n[1^n+\binom{n}{1}\left(\frac{\overline{ARM}}{A}\right)\frac{1}{(s+MR)}+\binom{n}{j}\left(\frac{\overline{ARM}}{A}\right)^j\left(\frac{1}{s+MR}\right)^j + \ldots + \binom{n}{n}\left(\frac{\overline{ARM}}{A}\right)^n\left(\frac{1}{s+MR}\right)^n] \qquad (A3)$$

where $\binom{n}{j} = n!/[(n-j)!j!]$.

Multiplication of the right side of (A3) by 1/s is equivalent to integration from 0 to t in the time domain. Hence, the contribution to the L[Pr[delay < or =t]]xR(nt^*) of the j^{th} term from (A3) will be $(AR)^n\binom{n}{j}\left(\frac{\overline{ARM}}{A}\right)^j\frac{1}{s}\left(\frac{1}{s+MR}\right)^j$. Expanding this term in terms of a partial fraction expansion produces

$$(AR)^n\binom{n}{j}\left(\frac{\overline{ARM}}{A}\right)^j\frac{1}{s}\left(\frac{1}{s+MR}\right)^j = (AR)^n\binom{n}{j}\left(\frac{\overline{ARM}}{A}\right)^j\left(\frac{1}{MR}\right)^j\left[\frac{1}{s}-\frac{(MR)^{j-1}}{[s+MR]^j}-\frac{(MR)^{j-2}}{[s+MR]^{j-1}}\cdots-\frac{1}{s+MR}\right].$$

Inverting the above transorm to the time domain yields

$$(AR)^n\binom{n}{j}\left(\frac{\overline{AR}}{AR}\right)^j[U(t)-\frac{(MRt)^{j-1}e^{-MRt}}{(j-1)!}-\frac{(MRt)^{j-2}e^{-MRt}}{(j-2)!}-\ldots\frac{(MRt)e^{1-MRt}}{1!}-e^{-MRt}]$$

which is of the form $(AR)^n \binom{n}{j} \left(\frac{\overline{AR}}{AR}\right)^j \left[1 - \sum_{k=0}^{j-1} e^{-MRt} \frac{(MRt)^k}{k!}\right]$

Therefore,

$$Pr[\text{delay} < \text{ or } = t] \times R(nt^*) = (AR)^n + \sum_{j=1}^{n} \binom{n}{j} (AR)^{n-j} (1-AR)^j \left(1 - \sum_{k=0}^{j-1} e^{-MRt} \frac{(MRt)^k}{k!}\right) \quad (A4)$$

One notes for n=1, (A4) reduces to equation (7) with T=0. For n=2

$$Pr[\text{delay} < \text{ or } = t] \times R(nt^*) = (AR)^2 + 2AR(1-AR)(1-e^{-MRt}) + (1-AR)^2 (1-e^{-MRt}(1+MRt)). \quad (A5)$$

The $(AR)^2$ term, which is also the initial value (t=0), represents the probability both packets are available and stay reliable over their respective intervals, t^*. The second term represents the two possible events that the first (or second) packet is available and stays reliable (AR), and that the second (or first) packet is not available and reliable (1-AR) and is repaired within time t and stays reliable $(1-e^{-MRt})$. The third term represents the event where both packets are not available and reliable and are repaired within interval t and stay reliable.

DISTRIBUTION LIST

STANDARD:

R100 - 2	R200 - 1
R102/R103/R103R - 1	R300 - 1
R102M - 1	R400 - 1
R102T - 9 (8 for stock)	R500 - 1
R104 - 1	R700 - 1
R110 - 1	R800 - 1
R123 - 1 (Library)	NCS-TS - 1
R124A - 1 (for Archives)	101A - 1
	312 - 1

* R102T - 12 (Unclassified/Unlimited Distribution)

DCA-EUR - 2 (Defense Communications Agency European Area
ATTN: Technical Library
APO New York 09131)

DCA-PAC - 3 (Commander
Defense Communications Agency Pacific Area
Wheeler AFB, HI 96854)

DCA SW PAC - 1 (Commander, DCA - Southwest Pacific Region
APO San Francisco 96274)

DCA NW PAC - 1 (Commander, DCA - Northwest Pacific Region
APO San Francisco 96328)

DCA KOREA - 1 (Chief, DCA - Korea Field Office
APO San Francisco 96301)

DCA-Okinawa - 1 (Chief, DCA - Okinawa Field Office
FPO Seattle 98773)

DCA-Guam - 1 (Chief, DCA - Guam Field Office
Box 141 NAVCAMS WESTPAC
FPO San Francisco 96630)

US NAV Shore EE PAC - 1 (U.S. Naval Shore Electronics Engineering
Activity Pacific, Box 130, ATTN: Code 420
Pearl Harbor, HI 96860)

1843 EE SQ - 1 (1843 EE Squadron, ATTN: EIEXM
Hickam AFB, HI 96853)

DCA FO ITALY - 1 (DCA Field Office Italy, Box 166
AFSOUTH (NATO), FPO New York 09524

USDCFO - 1 (Cnief, USDCFO/US NATO
APO New York 09667)

SPECIAL:

Office of the Assistant Secretary of Defense (C^3I), ATTN: Communications Systems, The Pentagon, Washington, D.C. 20301
Joint Chiefs of Staff, ATTN: TC3S, DCS Division, Washington, D.C. 20301
Headquarters, Department of the Army, ATTN: DAAC-NIS-SC, Washington, D.C. 20301
Navy C^2 Plans & Programs Division, Office of the Chief of Naval Operations, Department of the Navy, ATTN: OP-940, Washington, D.C. 20350
Headquarters, U.S. Air Force, ATTN: AF/XOKCP, HQ U.S. Air Force, Washington, D.C. 20330
Commandant of the Marine Corps, ATTN: CCP, Washington, D.C. 20380
Headquarters, U.S. Army Communications Command, ATTN: CC-OPS-P, Ft. Huachuca, AZ 85613
Naval Telecommunications Command, ATTN: Code 20 (Mr. Hall), 4401 Massachusetts Ave, Washington, D.C. 20390
Headquarters, Air Force Communications Command, ATTN: XOXO, Scott AFB, IL 62225
Commander-in-Chief, Aerospace Defense Command, ATTN: KRT, Peterson AFB, CO 80912
Commander-in-Chief, Europe, ATTN: J-6 (ECJ6-PP), APO New York 09128
Commander-in-Chief, Atlantic, ATTN: J-623B, Norfolk, VA 23511
Comm der-in-Chief, Military Airlift Command, ATTN: DOKX, Scott AFB, IL 62226
Commander-in-Chief, Pacific Command, ATTN: J-612A, Camp H.M. Smith, HI 96861
Commander-in-Chief, U.S. Readiness Command, ATTN: RCJ6-T (Mr. Jack Kunkle), MacDill AFB, FL 33608
Commander-in-Chief, Strategic Air Command, ATTN: SAC/DCXT, Offutt AFB, NE 68113
Commander-in-Chief, U.S. Southern Command, ATTN: SCCE, APO Miami 34003
Director, Defense Contract Audit Agency, Building 4, ATTN: H. Charles Teubner, Jr., Cameron Station, Alexandria, VA 22314
Commander, Defense Communications Agency European Area, ATTN: E400, APO New York 09131
Commander, Defense Communications Agency Pacific Area, ATTN: P300 (Mr. Yamada), Wheeler AFB, HI 96854
Director, Defense Security Assistance Agency, Washington, D.C. 20301
Director, Defense Intelligence Agency, ATTN: RSM-1, Washington, D.C. 20301
Director, Defense Logistics Agency, Eastern Regional Telecommunications Office (DERTO), c/o Defense General Supply Center, ATTN: Mr. Myers, Richmond, VA 23297
Director, Defense Mapping Agency, ATTN: Mr. Jones, Jr., Building 56, U.S. Naval Observatory, Washington, D.C. 20305
Director, Defense Nuclear Agency, ATTN: SOCM, Washington, D.C. 20150
Federal Emergency Management Agency, Office of Operations Support, ATTN: OS-WX, 1725 I Street, N.W., Washington, D.C. 20472
Director, National Security Agency, ATTN: S-03 (J. Flanagan), Ft. George G. Meade, MD 20755

Director, Joint Tactical Communications (TRI-TAC) Office, ATTN: TT-E-SD, (Mullins), 197 Hance Avenue, Tinton Falls, NJ 07724

Commander-in-Chief, U.S. Naval Forces, Europe, Box 6, APO New York 09510

DARCOM, ATTN: DRCCE-P, Alexandria, VA 22332

Commander, Naval Electronics Command, ATTN: PME 108 T2, Washington, D.C. 20360

U.S. Army Communications Command, ATTN: CCC-SEO, Ft. Huachuca, AZ 85613

Commander, U.S. Army CORADCOM, ATTN: DRDCO-SEI-E (S. Manno), Ft. Monmouth, NJ 07703

Commander-in-Chief, U.S. Air Force Europe, ATTN: DCX, APO New York 09012

Commander-in-Chief, U.S. Army, Europe, ATTN: AEAGC-CCIS, APO New York 09403

Commandant, USASC&FG, ATTN: ATZHCD-CS, Ft. Gordon, GA 30905

Chief, U.S. Defense Communications Field Office/U.S. NATO, APO New York 09667

Commander, 5th Signal Command, ATTN: CCE-OP-TD, APO New York 09056

Headquarters, Air Force Communications Command, 1842 EEG, ATTN: EETSA, Scott AFB, IL 62225

DAT

FILM