TDA Progress Report 42-106 August 15, 1991

# Stochastic Availability Analysis of Operational Data Systems in the Deep Space Network

T. N. Issa*
TDA Mission Support and DSN Operations

*Existing availability models of standby redundant systems consider only an operator's performance and its interaction with the hardware performance. In the case of operational data systems in the DSN, in addition to an operator–system interface, a controller reconfigures the system and links a standby unit into the network data-path upon failure of the operating unit. In this article, a stochastic (Markovian) process technique is employed to model and analyze the availability performance of this class of communication systems. The link-controller's performance and occurrence of degradation due to partial failures are quantitatively incorporated into the model. Exact expressions of the steady-state availability and proportion-degraded performance measures are derived for the systems under study. The interaction among the hardware, operator, and controller performance parameters and that interaction's effect on data availability are evaluated and illustrated for an operational data-processing system.*

## I. Introduction

Extensive research and practical literature exists in relation to the analysis of human performance and reliability modeling of man–machine systems. An up-to-date list and classification of the body of literature addressing human errors and their effect on the reliability and availability of engineering systems are provided in [1]. Human error is defined as a failure to perform a prescribed act (or an out-of-tolerance human action) that could result in damage to equipment or the disruption of scheduled operations [2,3]. Categories and causal analysis of human errors are detailed in [4–6].

Human performance is not easy to quantify and predict. Rigby [7] stated that error is a function of human variability; however, there are several other factors that may be considered in the analysis and quantitative measurement of human performance [8–10]. The problem of human reliability prediction has been discussed earlier by Meister [11] and Regulinski [12]. Recent studies, such as those of Dhillon [13–17] and Gupta [18,19] have emphasized reliability and availability modeling of standby systems with human-initiated failures. In these efforts, the Markov pro-

---

*Bendix Field Engineering Corporation

cess was employed to model the interaction of hardware and human performances. In these models, hardware units of only two states (operating and failed) were considered, and the impact of one type of human interface was incorporated, that is, the performance of operating personnel only. One assumption common to these models is that the switch over to a standby unit (i.e., restoration of system operation) is instantaneous and perfect.

In the telecommunication and data-processing systems implemented in the ground-based communication complexes of the DSN, there are two types of human–equipment interface. One type of interface involves an operator's monitor and control of an operational unit, and the second type requires a link controller's interface with a console display to perform system reconfiguration and restoration by linking a standby unit. Operator errors may cause failure (disruption of operation) or performance degradation of the operating unit. Errors made by the link controller would usually increase the completion time of the reconfiguring and linking task.

In this study, the stochastic operational behavior of two-unit standby data-processing systems at the DSN is investigated. In addition to operator-initiated outages, these systems are characterized by a noninstantaneous restoration of their operation through a controller-performed linking process. The purpose of this analysis is to apply a Markov process technique to develop steady-state expressions for "operational" availability and proportion-degraded performance estimation and to implement them as relevant measures of performance for the systems under study. Of particular significance is the evaluation of the impact of various levels of link-controller performance on the proposed performance measures at selected levels of operator error rate.

## II. The Human Role in Data-Processing Systems Operation and Maintenance

In this study, a class of communication systems utilized during spacecraft tracking and data acquisition is defined. This class includes such systems as the receiver, telemetry processing, command assemblies, and others. A typical two-unit standby configuration used in ground-based stations is considered representative of these systems for reliability and availability modeling.

In any configuration, an "operational" unit or assembly is viewed as a complex structure of hardware and human components. The human components and their activities include:

1. *Operator:* Performs time-continuous operation and monitoring of equipment. The operator provides inputs and responses, performs tests and verifications, and monitors the operating unit.

2. *Link controller:* Performs system reconfiguration and standby-unit linking upon failure of the operating unit. The link controller interfaces with a console display to monitor data flow and link status parameters, and communicates with the operator when displayed messages indicate problems.

Possible error categories associated with these human components and their tasks include:

1. *Operator errors:* Errors of memory, errors of identification and interpretation, and the cumulative impact of errors of operation [6,7].

2. *Link controller errors:* Errors of attention, errors of interpretation, errors of procedure and documentation, and errors of communication.

The levels of maintenance associated with the systems under study include the following:

1. *Level 1 maintenance:* This is performed mainly by the link controller following an initial diagnosis and report of anomalous condition by the operator. It requires the controller to provide a sequence of inputs or directives contained within an application software to accomplish system reconfiguration and linking of a standby unit into the operating path (i.e., system restoration). The reconfiguration and link completion time is an indicator of the controller's level of performance.

2. *Level 2 maintenance:* This is performed on site by maintenance personnel equipped with diagnostic and test capabilities. It involves diagnosis and fault isolation within the malfunctioning unit, removal and replacement of the faulty component, and verification of proper functioning of the repaired unit.

## III. Data-Processing Systems Reliability Definitions and Measures

Most reliability definitions and concepts used in the classical reliability area are applicable to data-processing systems analysis. However, there are a few terms that are particularly pertinent. A brief description of these terms (to appear in the model) follows.

The *system outage* occurs when both units in the standby configuration are disconnected for repair from various failure modes.

A *temporary outage* occurs when one unit has failed and the link controller is involved in the reconfiguration and linking task to restore system operation.

*Degraded* refers to a unit's performance characterized by a full-capacity throughput associated with a higher error rate per data block.

*System degraded* occurs when an operating unit has become degraded for which the standby unit is inoperable.

*Temporary degraded* occurs when the operating unit is in a degraded mode and the link controller is involved in restoring system operation.

An integrated operational analysis of the data systems under study requires that all their aspects of behavior, which have been described earlier, need to be considered. Therefore, formal reliability analysis and modeling of these systems have been conducted and some of the relevant performance measures have been derived. Satisfactory system performance from the customer's point of view, namely, that of the using spacecraft, is affected by frequencies and durations of outages and degraded output. Thus, adequate measures of reliability may include the proportions of normal data and degraded data acquired, "combined" data availability, and the probability of system outage due to human errors. In the subsequent sections, the Markov process technique is employed to derive exact expressions for some of these performance measures.

## IV. Model Description and Assumptions

The following are the specific assumptions of the proposed Markov model:

1. The model represents a two-unit identical standby redundant system with operator-initiated failure and degraded states.
2. The operating unit may fail due to either a hardware fault or an operator error. The unit may also operate in a degraded mode due to partial hardware failures and/or noncritical operator errors.
3. Various failure modes are statistically independent.
4. Hardware and operator-initiated failure rates, as well as the degradation rate, are all constants.
5. The link controller performs the reconfiguration and linking process. The completion time of this process is exponentially distributed.
6. The physical repair of the failed or degraded unit (level-2 maintenance) is undertaken as soon as the reconfiguration and linking task is completed. The repaired unit is recovered directly to the fully operable or operating mode.
7. Repair rates (i.e., level-2 maintenance completion rates) from various failure modes are constants.
8. System operating policies require that the degraded unit of the system must not be repaired at its degraded output during the linking process of the standby unit.
9. The degraded unit of the system is regarded as failed (due to hardware or human-initiated failures) when providing degraded-unusable output; that is, when the error rate per data block is greater than a previously specified criterion or tolerance limit.
10. The failure rate of a unit in its standby mode is zero.
11. A unit may exist in one of three possible states—operating, degraded, or failed (with total output loss).
12. Initially, the system is in the fully operating state with one unit being in an operable standby mode.
13. During system operation, only one change can take place in the state of the system at each instantaneous change or increment of time.

## V. Model Development

### A. Notation List

The state-space diagram associated with the two-unit standby human-machine system is shown in Fig. 1. The following symbols are associated with this system model:

$S_i$ denotes the $i$th state of the system, for $i = 0, 1, 2, \cdots, 15$; $i = 0$ (one unit is operating, the other unit is in standby mode); $i = 1$ (one unit has failed due to a hardware failure); $i = 2$ (one unit failed due to an operator error); $i = 3$ (one unit is in a degraded state); $i = 4, 5, 6$ (one unit is linked, the other unit is under repair from a failure mode); $i = 7, 8, 9$ (one unit is under repair from a failure mode, the other unit is in a degraded state); $i = 10$ (both units are under repair due to hardware failures); $i = 11, 12$ (both units are under repair—one from a hardware failure and the other from an operator-initiated failure); $i = 13$ (both units are under repair from operator-initiated failures); $i = 14, 15$ (both units are under repair—one from a degraded mode, the other from a hardware failure and operator-initiated failure, respectively)

$P_i(t)$ denotes the probability that the system is in state $S_i$ at time $t$, for $i = 0, 1, 2, \cdots, 15$.

$\lambda_j$ is the constant failure or degraded rate of a unit due to the $j$th failure mode, where $j = 1, 2, 3$, corresponding to hardware failure, operator-initiated failure, and degraded modes, respectively.

$\lambda'_j$ is the constant failure rate of the degraded unit due to the $j$th failure mode, where $j = 1, 2$, corresponding to hardware and human-initiated failure modes, respectively.

$\lambda_{Lj}$ is the link controller's completion rate of the linking task of the standby unit given the $j$th failure mode, where $j = 1, 2, 3$, corresponding to hardware failure, operator-initiated failure, and degraded failure modes, respectively. That is, the link controller's completion rate of the level-1 maintenance task.

$\mu_j$ is the constant repair rate of a failed unit from the $j$th failure mode, where $j = 1, 2, 3$, corresponding to the hardware failure, operator-initiated failure, and degraded modes, respectively.

$\mu_4, \mu_5$ are the constant repair rates of either one of the two failed units from hardware failure and operator-initiated failure modes, respectively, that is, $\mu_4 = 2\mu_1$ and $\mu_5 = 2\mu_2$.

### B. Model Formulation

The following differential equations were developed by examining the discrete-space stochastic process described in Fig. 1:

$$P'_0(t) = -(\lambda_1+\lambda_2+\lambda_3)P_0(t)+\mu_1 P_4(t)+\mu_2 P_5(t)+\mu_3 P_6(t)$$

$$P'_1(t) = \lambda_1 P_0(t) - \lambda_{L1} P_1(t) + \lambda'_1 P_3(t)$$

$$P'_2(t) = \lambda_2 P_0(t) - \lambda_{L2} P_2(t) + \lambda'_2 P_3(t)$$

$$P'_3(t) = \lambda_3 P_0(t) - (\lambda_{L3} + \lambda'_1 + \lambda'_2) P_3(t) + \mu_1 P_7(t)$$

$$+ \mu_2 P_8(t) + \mu_3 P_9(t)$$

$$P'_4(t) = \lambda_{L1} P_1(t) - (\lambda_1 + \lambda_2 + \lambda_3 + \mu_1) P_4(t)$$

$$+ \mu_4 P_{10}(t) + \mu_2 P_{12}(t) + \mu_3 P_{14}(t)$$

$$P'_5(t) = \lambda_{L2} P_2(t) - (\lambda_1 + \lambda_2 + \lambda_3 + \mu_2) P_5(t)$$

$$+ \mu_1 P_{11}(t) + \mu_5 P_{13}(t) + \mu_3 P_{15}(t)$$

$$P'_6(t) = \lambda_{L3} P_3(t) - (\lambda_1 + \lambda_2 + \lambda_3 + \mu_3) P_6(t)$$

$$+ \mu_1 P_{14}(t) + \mu_2 P_{15}(t)$$

$$P'_7(t) = \lambda_3 P_4(t) - (\lambda'_1 + \lambda'_2 + \mu_1) P_7(t)$$

$$P'_8(t) = \lambda_3 P_5(t) - (\lambda'_1 + \lambda'_2 + \mu_2) P_8(t)$$

$$P'_9(t) = \lambda_3 P_6(t) - (\lambda'_1 + \lambda'_2 + \mu_3) P_9(t)$$

$$P'_{10}(t) = \lambda_1 P_4(t) + \lambda'_1 P_7(t) - \mu_4 P_{10}(t)$$

$$P'_{11}(t) = \lambda_1 P_5(t) + \lambda'_1 P_8(t) - \mu_1 P_{11}(t)$$

$$P'_{12}(t) = \lambda_2 P_4(t) + \lambda'_2 P_7(t) - \mu_2 P_{12}(t)$$

$$P'_{13}(t) = \lambda_2 P_5(t) + \lambda'_2 P_8(t) - \mu_5 P_{13}(t)$$

$$P'_{14}(t) = \lambda_1 P_6(t) + \lambda'_1 P_9(t) - (\mu_1 + \mu_3) P_{14}(t)$$

$$P'_{15}(t) = \lambda_2 P_6(t) + \lambda'_2 P_9(t) - (\mu_2 + \mu_3) P_{15}(t) \qquad (1)$$

with the following initial conditions at time $t = 0$:

$$P_0(0) = 1, \qquad P_i(0) = 0, \qquad \text{for } i = 1, 2, \cdots, 15 \qquad (2)$$

## VI. Solution of the Model

Considering the limiting or steady-state probabilities, the derivatives in the first set of equations (1) are set to zero. The relationship, $P_0 + P_1 + \cdots + P_{15} = 1$ is then utilized to obtain the following steady-state expressions:

$$P_i = K_i P_0, \qquad \text{for } i = 1, 2, \cdots, 15 \qquad (3)$$

and

$$P_0 = \frac{1}{1 + K_1 + K_2 + \cdots + K_{15}} \tag{4}$$

where $K_i$ is a constant associated with state $i$ and defined as follows:

$$K_1 = \frac{\lambda_1 + \lambda'_1 K_3}{\lambda_{L1}}, \quad K_2 = \frac{\lambda_2 + \lambda'_2 K_3}{\lambda_{L2}}$$

$$K_3 = \left( \frac{a b_4 b_6 + \lambda_1 \mu_1 b_6 + \lambda_2 \mu_2 b_4}{m_1 b_4 b_6 + \mu_1 m_3 b_6 + \mu_2 m_4 b_4} \right)$$

$$K_4 = \frac{-(\lambda_1 + m_3 K_3)}{b_4}, \quad K_5 = \frac{-(\lambda_2 + m_4 K_3)}{b_6}$$

$$K_6 = \frac{-\lambda_{L3} K_3}{b_8}, \quad K_7 = \frac{\lambda_3 K_4}{a_5}$$

$$K_8 = \frac{\lambda_3 K_5}{a_6}, \quad K_9 = \frac{\lambda_3 K_6}{a_7}$$

$$K_{10} = \left( \frac{\lambda_1}{\mu_4} + \frac{\lambda_3 \lambda'_1}{a_5 \mu_4} \right) K_4, \quad K_{11} = \left( \frac{\lambda_1}{\mu_1} + \frac{\lambda_3 \lambda'_1}{a_6 \mu_1} \right) K_5$$

$$K_{12} = \left( \frac{\lambda_2}{\mu_2} + \frac{\lambda_3 \lambda'_2}{a_5 \mu_2} \right) K_4, \quad K_{13} = \left( \frac{\lambda_2}{\mu_5} + \frac{\lambda_3 \lambda'_2}{a_6 \mu_5} \right) K_5$$

$$K_{14} = \left( \frac{\lambda_1}{a_8} + \frac{\lambda_3 \lambda'_1}{a_7 a_8} \right) K_6, \quad K_{15} = \left( \frac{\lambda_2}{a_9} + \frac{\lambda_3 \lambda'_2}{a_9 a_7} \right) K_6$$

$$m_1 = \frac{\lambda_{L3} \mu_3}{b_8}, \quad m_2 = \frac{a_1 b_8 + \lambda_{L3} b_3}{b_8}$$

$$m_3 = \frac{\lambda'_1 b_8 - \lambda_{L3} b_5}{b_8}, \quad m_4 = \frac{\lambda'_2 b_8 - \lambda_{L3} b_7}{b_8}$$

$$b_1 = \frac{\lambda_3 \mu_1}{a_5}, \quad b_2 = \frac{\lambda_3 \mu_2}{a_6}, \quad b_3 = \frac{\mu_3 \lambda_3}{a_7}$$

$$b_4 = \frac{\lambda_3 \lambda'_1 + \lambda_3 \lambda'_2 + \lambda_1 a_5 + \lambda_2 a_5 - a_2 a_5}{a_5}$$

$$b_5 = \frac{\lambda_1 \mu_3 a_7 + \lambda_3 \lambda'_1 \mu_3}{a_7 a_8}$$

$$b_6 = \frac{\lambda_3 \lambda'_1 + \lambda_3 \lambda'_2 + \lambda_1 a_6 + \lambda_2 a_6 - a_3 a_6}{a_6}$$

$$b_7 = \frac{\lambda_2 \mu_3 a_7 + \mu_3 \lambda_3 \lambda'_2}{a_7 a_9}$$

$$b_8 = \frac{(\mu_2 \lambda_3 \lambda'_2 + \mu_2 \lambda_2 a_7)}{a_7 a_9} + \frac{(\lambda_3 \lambda'_1 \mu_1 + \mu_1 \lambda_1 a_7)}{a_7 a_8} - a_4$$

$$a = \lambda_1 + \lambda_2 + \lambda_3, \quad a_1 = \lambda_{L3} + \lambda'_1 + \lambda'_2, \quad a_2 = a + \mu_1$$

$$a_3 = a + \mu_2, \quad a_4 = a + \mu_3, \quad a_5 = \lambda'_1 + \lambda'_2 + \mu$$

$$a_6 = \lambda'_1 + \lambda'_2 + \mu_2, \quad a_7 = \lambda'_1 + \lambda'_2 + \mu_3, \quad a_8 = \mu_1 + \mu_3$$

$$a_9 = \mu_2 + \mu_3$$

The steady-state probabilities given in Eqs. (3) and (4) can be used to develop system availability and reliability measures. These measures include:

1. Integrated steady-state availability denoted by $A_S$. This measure combines both normal and degraded availabilities and is given by

$$A_S = (1 + K_3 + K_4 + K_5 + K_6 + K_7 + K_8 + K_9) P_0 \tag{5}$$

2. The proportion of normal-performance, $P_N$, is given by

$$P_N = (1 + K_4 + K_5 + K_6) P_0 \tag{6}$$

3. The proportion of degraded-performance, $P_D$, is given by

$$P_D = (K_3 + K_7 + K_8 + K_9) P_0 \tag{7}$$

4. The probability of system failure (data outage) due to the cumulative impact of human errors, $P_H$, is given by

$$P_H = (K_{12} + K_{13} + K_{15}) P_0 \tag{8}$$

Equations (5) through (8) define the proposed availability model of the human–machine standby processing system.

## VII. Application and Analysis

The steady-state availability model described in Eqs. (5) through (8) was implemented to evaluate the "operational" performance of several standby data-processing systems. The receiver, subcarrier demodulator assembly, and telemetry processing assembly (TPA) are examples of these systems. They are utilized in spacecraft-to-station communications at each Deep Space Communications Complex. The following two applications demonstrate the usefulness of some of these measures for performance analysis of a TPA assembly as a selected configuration.

### A. Steady-State Availability Analysis

For the application of the availability measure given by Eq. (5) to the TPA assembly, integrated data availability was computed for the following specified parametric values:

$\lambda_1 = 0.02$ failure/hr, $\mu_1 = 0.3$ repair/hr

$\lambda_2 = 0.002$ to $0.03$ failure/hr, $\mu_2 = 0.3$ repair/hr

$\lambda_3 = 0.006$ failure/hr, $\mu_3 = 0.2$ repair/hr

$\lambda_1' = 0.002$ failure/hr, $\mu_4 = 2\mu_1$

$\lambda_2' = 0.003$ failure/hr, $\mu_5 = 2\mu_2$

$\lambda_{L1} = 3.0$ link/hr by link controller

$\lambda_{L2} = 0.5$ to $3.0$ link/hr by link controller

$\lambda_{L3} = 4.0$ link/hr by link controller

The numerical results pertaining to Eq. (5) indicate variation in the TPA system availability, which is described in Fig. 2. The plots demonstrate that TPA-integrated data availability decreases with increasing levels of operator-initiated outage rate $\lambda_2$ and decreasing levels of the corresponding completion rate of reconfiguration and linking $\lambda_{L2}$.

If the TPA operational availability requirement is 98.5 percent, then possible combinations of hardware and human reliability requirements include:

$\lambda_2 = 0.002$, $\lambda_{L2} = 1$, $\lambda_1 = 0.02$, and other parameters remain the same

$\lambda_2 = 0.004$, $\lambda_{L2} = 2$, $\lambda_1 = 0.02$, and other parameters remain the same

Thus, operational availability can be achieved and/or improved through a proper trade-off among operator error rate, link completion rate (or level-1 maintenance completion rate), and hardware failure rate. The optimal combination of reliability parameters (to be considered for future design reviews) is usually selected based on whether improvements are needed in the hardware area, operating personnel area, or both.

### B. Degraded-Performance Analysis

The proportion of the degraded-performance measure given by Eq. (7) is applied to the TPA system by using the previously specified parametric values, except for the following parameters:

$\lambda_2 = 0.03$ failure/hr, $\lambda_{L1} = \lambda_{L2} = 4.0$ link/hr

$\lambda_3 = 0.002$ to $0.03$ failure/hr,

$\lambda_{L3} = 0.5$ to $3.0$ link/hr

The pertinent numerical results indicate variation in the TPA annual degraded duration, which is plotted in Fig. 3. The plots demonstrate how system-degraded duration increases when a unit partial failure rate $\lambda_3$ increases, and the corresponding completion rate of reconfiguration and linking $\lambda_{L3}$ decreases.

If the TPA annual degraded throughput is desired not to exceed a total of 200 hours, then possible combinations of the required partial failure rate (i.e., degradation rate) and controller's completion rate of the reconfiguration task include, where other parameters remain the same:

$\lambda_3 \leq 0.006$ , $\lambda_{L3} \geq 0.5$

$\lambda_3 \leq 0.010$ , $\lambda_{L3} \geq 1.0$

When system-degraded performance occurs, the reconfiguration and linking process is usually performed carefully or delayed for some time (provided that data throughput remains usable-degraded); therefore, $\lambda_{L3}$ is most frequently less than or equal to 1 link/hr. Thus, greater attention should be given to maintain $\lambda_3$ below 0.010 failure/hr. This can be achieved through improvements of assembly design and its human interface and operational characteristics in order to reduce frequencies of partial failures and noncritical operating errors.

The other system performance measures, including the proportion of normal-performance and the probability of data outage due to human errors, are given by Eqs. (6) and (8), respectively. These measures can be applied to the TPA system in a similar fashion by using selected parametric values. The variation in each measure as compared with the changing levels of $\lambda_2$ and $\lambda_{L2}$ can also be graphically demonstrated. It should be obvious that the proportion of normal-performance data acquired $P_N$ constitutes a significant portion of integrated (normal and degraded) data availability $A_S$. On the other hand, increasing operator error rate $\lambda_2$ results in a higher probability of system failure due to operator errors.

The graphical and parametric analyses of the proposed model, as described earlier, allow for presenting the practical aspects of the model and assist in the interpretation of the results.

## VIII. Conclusions

This article presented a stochastic (Markovian) availability analysis of a class of human–machine communication standby systems, namely, data-processing systems. In the developed model, the possibility of a degraded-performance occurrence was considered and the human task of noninstantaneous restoration of system operation was incorporated. Therefore, the proposed model is more general and adequate for the systems under study than existing models.

The steady-state performance expressions derived in this study can be used in conjunction with appropriate plots to facilitate various failure mode sensitivities and trade-off analysis. Such analysis would support the decision-making process with regard to the optimal combination of the operator-error rate, the hardware failure rate, and the system restoration rate, which may result in a system "operational" availability that meets or exceeds a prespecified requirement.

## Acknowledgments

The author would like to thank Joseph P. Goodwin of the TDA Mission Support and DSN Operations Office for his encouragement and support of this study. In addition, gratitude is due to N. Hoang for providing actual system performance data samples from the Discrepancy Report System to compute failure and restoration rates, and to the operating and maintenance personnel of the Goldstone Deep Space Communications Complex for the initial guidance and useful discussions related to the performance modeling of operational data systems.

## References

[1] K. W. Lee, F. A. Tillman, and J. J. Higgins, "A Literature Survey of the Human Reliability Component in a Man–Machine System," *IEEE Trans. Reliability*, vol. R-37, pp. 24–34, 1988.

[2] G. W. Nieuwhof, "Short Note—Human Error," *Reliability Engineering*, vol. 6, pp. 191–192, 1983.

[3] B. S. Dhillon, *Human Reliability With Human Factors*, New York: Pergamon Press, 1986.

[4] D. Meister, "The Problem of Human-Initiated Failures," *Eighth National Symposium on Reliability and Quality Control*, pp. 469–476, 1962.

[5] L. H. Nawrocki, M. H. Strub, and R. M. Cecil, "Error Categorization and Analysis in Man–Computer Communication Systems," *IEEE Trans. Reliability*, vol. R-22, pp. 135–140, 1973.

[6] T. N. Issa, *Availability Prediction of Human-Equipment Data-Flow Systems With Application to NASA Deep Space Station*, Ph.D. dissertation, The Wichita State University, Wichita, Kansas, 1990.

[7] L. V. Rigby, "The Nature of Human Error," *Proc. Ann. Tech. Conf. of ASQC*, pp. 457–465, 1970.

[8] A. D. Swain, "Some Problems in the Measurement of Human Performance in Man–Machine Systems," *Human Factors*, vol. 6, pp. 687–700, 1964.

[9] J. A. Adams, "Issues in Human Reliability," *Human Factors*, vol. 24, pp. 1–10, 1982.

[10] J. A. Adams, *Human Factors Engineering*, New York: Macmillan, 1989.

[11] D. Meister, "Methods of Predicting Human Reliability in Man–Machine Systems," *Human Factors*, vol. 6, pp. 621–646, 1964.

[12] T. Regulinski and W. Askren, "Stochastic Modeling of Human Performance Effectiveness Functions," *Proc. Ann. Reliab. Maint. Symp.*, pp. 407–416, 1972.

[13] B. S. Dhillon and R. Misra, "Effect of Critical Human Error on System Reliability," *Reliability Engineering*, vol. 12, pp. 17–33, 1985.

[14] B. S. Dhillon and S. Rayapati, "Analysis of Redundant Systems With Human Errors," *Proc. Ann. Reliab. Maint. Symp.*, pp. 315–321, 1985.

[15] B. S. Dhillon and S. Rayapati, "Reliability Analysis of Non-Maintained Parallel Systems Subject to Hardware Failure and Human Error," *Microelectronics and Reliability*, vol. 25, pp. 111–122, 1985.

[16] B. S. Dhillon and S. Rayapati, "Human Error and Common-Cause Failure Modeling of Redundant Systems," *Microelectronics and Reliability*, vol. 26, pp. 1139–1162, 1986.

[17] B. S. Dhillon and S. Rayapati, "Human Error and Common-Cause Failure Modeling of Standby Systems," *Maint. Manag. Internat.*, vol. 7, pp. 93–110, 1988.

[18] P. P. Gupta and A. Kumar, "Reliability and MTTF Analysis of a Non-Repairable Parallel Redundant Complex System Under Hardware and Human Failures," *Microelectronics and Reliability*, vol. 26, pp. 229–234, 1986.

[19] P. P. Gupta and A. Kumar, "Stochastic Behavior of a Two-Unit Cold Standby Redundant Electronic Equipment Under Human Failure," *Microelectronics and Reliability*, vol. 27, pp. 15–18, 1987.

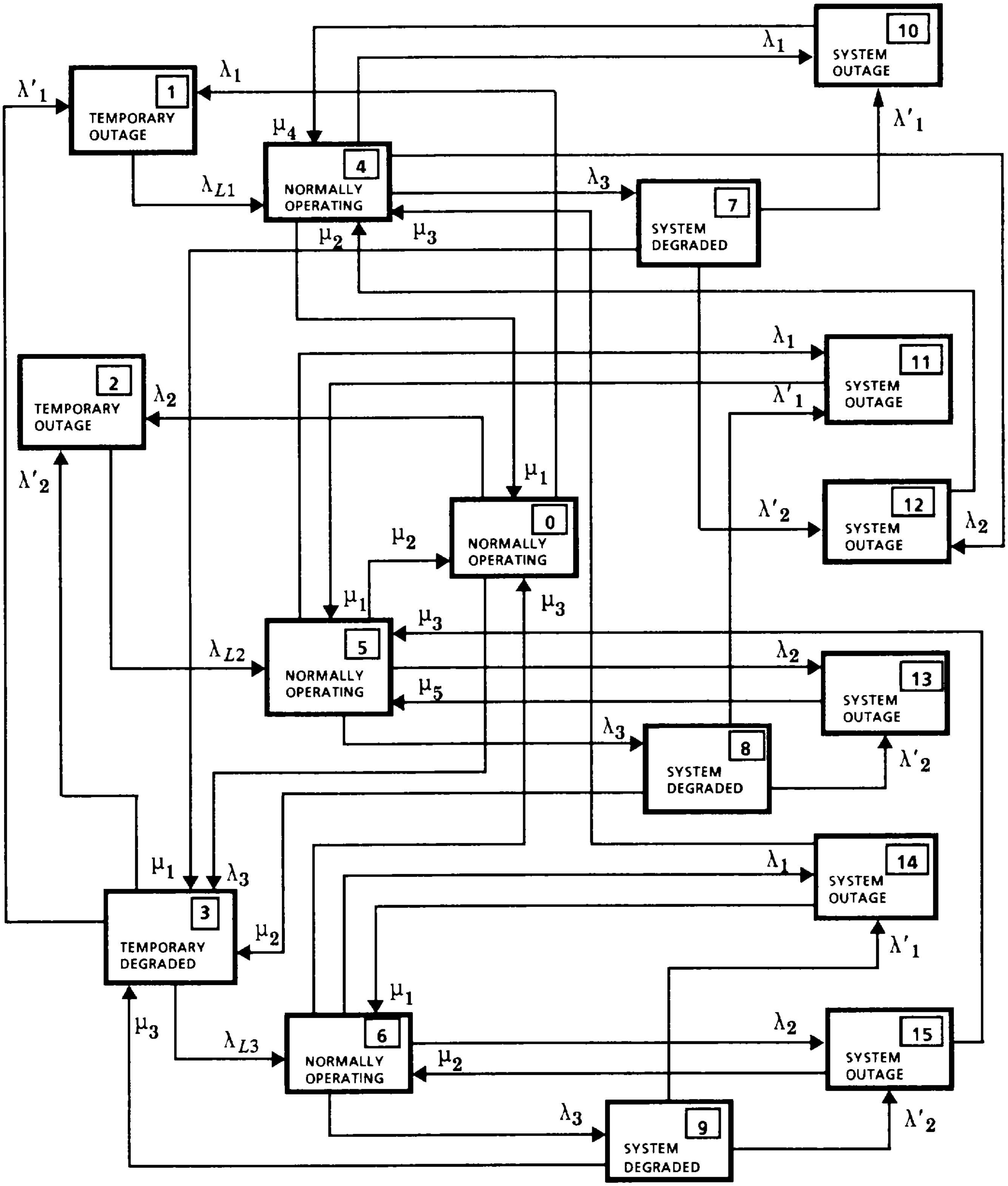

Fig. 1. State-space diagram of system stochastic performance.

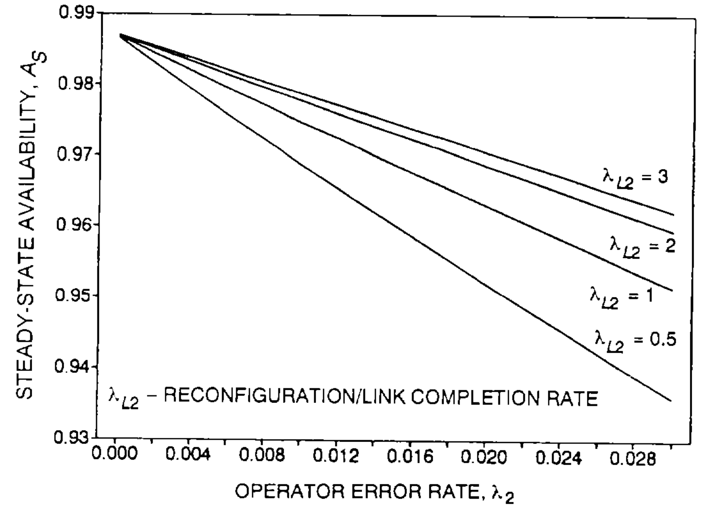

**Fig. 2. TPA integrated data availability versus operator error rate.**

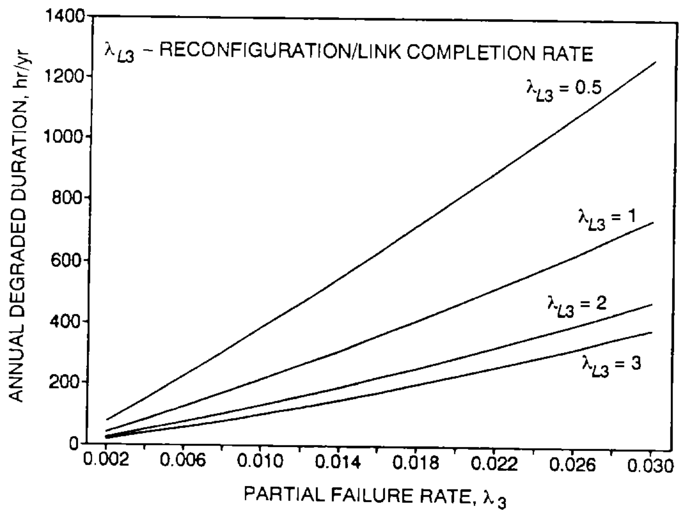

**Fig. 3. TPA annual degraded performance versus partial failure rate.**