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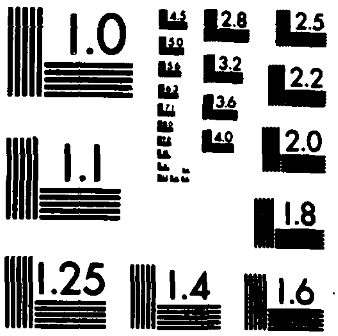

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NATIONAL COMMUNICATIONS SYSTEM

NETWORK LEVEL EMP EFFECTS SENSITIVITY STUDY ON SELECTED TELECOMMUNICATIONS EQUIPMENT

MARCH 27, 1987

OFFICE OF THE MANAGER,
NATIONAL COMMUNICATIONS SYSTEM
WASHINGTON, D.C. 20305

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The EMP Mitigation Program uses a network level approach to assess EMP effects on network performance. The approach is twofold. First, the effects of EMP on network equipment are obtained. The OMNCS has made EMP test program results available on the 1ESS and 5ESS switches; the TD-2 microwave, L4 carrier, T1 carrier, and FT3C fiber optic transmission systems; and the D4 channel bank. Second, the performance of the network exposed to EMP is characterized. This is accomplished by combining the equipment test program results with the network topology. A computer model, predicated on a statistical interpretation of EMP test data, processes this information and calculates a metric to characterize network performance. The model is run multiple times in a Monte Carlo process to calculate probabilistically the point-pair connectivity metric. Point-pair connectivity is a measure of the surviving connections with respect to the original connections. In estimating network performance the model acknowledge fundamental uncertainties in the supporting input data.

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EXECUTIVE SUMMARY

(U) The EMP Mitigation Program uses a network level approach to assess EMP effects on network performance. The approach is twofold. First, the effects of EMP on network equipment are obtained. The OMNCS has made EMP test program results available on the 1ESS and 5ESS switches; the TD-2 microwave, L4 carrier, T1 carrier, and FT3C fiber optic transmission systems; and the D4 channel bank. Second, the performance of the network exposed to EMP is characterized. This is accomplished by combining the equipment test program results with the network topology. A computer model, predicated on a statistical interpretation of EMP test data, processes this information and calculates a metric to characterize network performance. The model is run multiple times in a Monte Carlo process to calculate probabilistically the point-pair connectivity metric. Point-pair connectivity is a measure of the surviving connections with respect to the original connections. In estimating network performance the model acknowledges fundamental uncertainties in the supporting input data.

(U) INVESTIGATION

(U) This analysis has three main objectives:

- To evaluate the affect of the 4ESS switch, the D4 channel bank, and the microwave transmission facilities on network performance
- To develop an accurate network equipment data base for more comprehensive analyses
- To extend prior work on modelling network physical connectivity to network logical connectivity.

All of these goals were attained during the course of this study.

(U) Three types of telecommunications equipment are evaluated in this sensitivity study: 4ESS switches, D4 channel banks, and microwave transmission facilities. These equipment are discussed below.

- The 4ESS switch is the most prevalent switch in the toll network. However, no test data exists to descibe its behavior in an EMP stressed environment.
- Even as the importance of the D4 channel bank, an analog/digital interface, decreases as the network

migrates digitally, it is still considered a critical PSN equipment type for the foreseeable future.

- Microwave transmission facilities are selected for the sensitivity study because (1) they are widely used within the network and (2) the test data is only available on an older analog vacuum tube type system.

(U) The network addressed in this EMP effects analysis is the toll portion of the post-divestiture AT&T network. This network represents an accurate and current description of a major portion of the PSN. This data base is the most comprehensive available one to date, and has been extensively studied and processed to support detailed analyses.

(U) In this analysis three point-pair connectivity metrics are calculated, physical, baseline and NETS. Surviving switches are deemed physically connected so long as there is a path of surviving transmission facilities interconnecting them. The baseline and NETS are with respect to logical connectivity, i.e. there must be a physical connection and the network must have the operational capability to support communications over the physical connection. The grade of service received by network users is dictated by logical connectivity. The baseline logical connectivity represents the service provided by the PSN in its present form, while NETS connectivity is the service received with an enhanced routing capability.

(U) NETWORK LEVEL COMPUTER MODELING

(U) Three tasks are performed in the network level approach. First, the Network Connectivity Analysis Model (NCAM) generates a network topology consisting of the switches and transmission facilities that comprise the post-divestiture AT&T toll portion of the PSN. The second function of the approach is to determine which elements of the network will survive an EMP disturbance. This is performed by the Bayesian Survivability Model (BSM), which is based on Bayesian statistical theory. The third task is to calculate the point-pair connectivity metric to quantify network performance following the simulated EMP disturbance. Both physical and logical connectivity (PSN baseline and NETS) are calculated by NCAM using the point-pair metric.

(U) These three tasks are replicated fifty (50) times for three uniform stress levels, and are always based on the same statistical and probabilistic input data. The three stress levels are, 10-30 kV/m (low), 30-50 kV/m (medium) and 50-70 kV/m (high). This approach is known as the Monte Carlo procedure. For each replication in the Monte Carlo procedure, the network connectivity metric is computed. At the conclusion of the Monte Carlo process, two primary statistics are calculated, the mean and the standard deviation of the point-pair connectivity replications.

(U) SENSITIVITY ANALYSIS

(U) A sensitivity study is performed to determine the dependence of the network connectivity (physical, baseline and NETS) on the behavior of a particular equipment in the network. The degree of sensitivity of the network connectivity to the equipment under study is useful when determining key communications facilities in a network. This analysis is generally conducted when little or no data are available to describe the behavior of a network equipment exposed to EMP. The analysis procedure is as follows. First, the element addressed in the sensitivity study is assigned a range of discrete survivability values where each value describes the probability that the element survives an EMP stress. Second, the BSM determines which of the remaining elements survive the EMP stress level. Third, the network connectivity for the simulated stress level is obtained by the NCAM. After the Monte Carlo procedure, the mean and standard deviation of the network connectivity are calculated for the three EMP stress levels: low, medium, and high.

(U) In summary, this analysis is conducted under the following set of conditions:

- A sensitivity study is conducted on the effects of 4ESS switch, D4 channel bank, and microwave transmission facility survivability on network performance.

- The sensitivity of each equipment is calculated at three EMP stress level ranges -- low 10-30 kV/m, medium 30-50 kV/m, and high 50-70 kV/m.

- At each stress level a Monte Carlo process of 50 simulations is conducted. The result of the 50 simulations is the mean and standard deviation of network connectivity.

- Network connectivity is defined in terms of point-pair connectivity.

- The network analyzed is composed of 344 switches and the transmission facilities to which those switches are interconnected. The point-pair connectivity metric is calculated for the 124 Point-of-Presence switches (POPs) of the network. This is a valid approach as each user relies on a single POP for toll level communications.

(U) Before interpreting the results that are presented it is important to understand the assumptions which were necessary to conduct this analysis. The network analyzed is composed of many different types of switches and transmission facilities. However, the OMNCS only has EMP test data on seven of these equipment types. Equipment types for which no EMP test data are available are assigned the survivability characteristics of the equipment type they most technically resemble that has been tested. Therefore, each network equipment type is assigned the survivability of one of the seven equipment types that have been tested. This assignment process produces an unquantified source of error in the results.

(U) Another source of error is the test data itself. The equipment EMP tests were conducted by a variety of government agencies, for different purposes, and under different test conditions. The network level approach requires that this data be viewed by a consistent format. An interpolation procedure was therefore required to interpret this array of data into the consistent format, producing additional error.

Non-Sensitivity Study

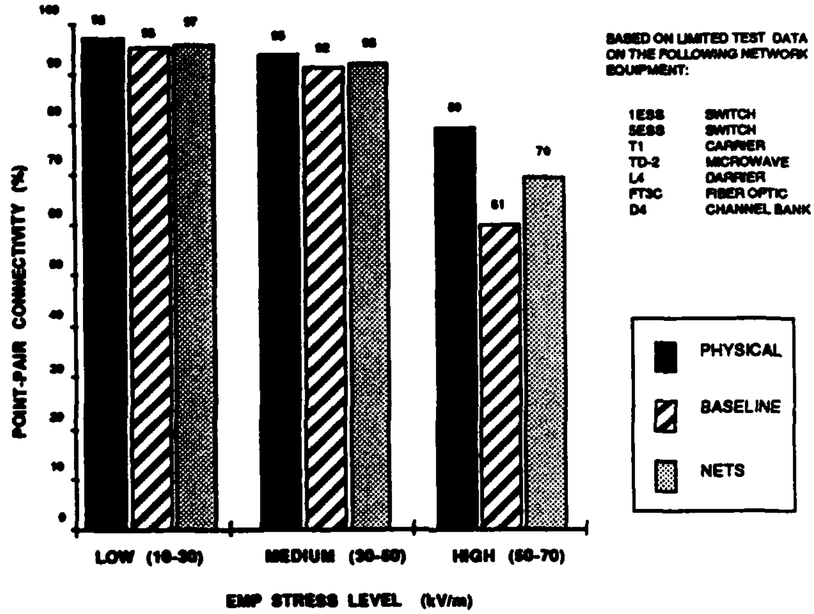
(U) Initially, a non-sensitivity studies was conducted. This implies that each equipment survived according to one of the seven equipment which have been EMP tested. The results of these simulations are presented in Exhibit ES-1.

(U) Within each group, the solid bar represents physical, the striped bar represents PSN baseline, and the dotted bar represents NETS mean point-pair connectivity following the 50 Monte Carlo simulations. Note that in the low and medium stress level bins the degradation effects appear to be minimal. The reason for this is that the EMP test data reflect very few equipment failures at these two levels. Since few equipment fail, both the physical and PSN baseline connectivities remain high. In such situations, from solely an EMP perspective, there does not appear to be a need for the NETS. The advantages of the NETS routing enhancement become apparent as a greater proportion of equipment fail, which occurs at the high stress level. As NETS makes greater use of surviving physical resources at this level, the logical connectivity improves from 61 percent to 70 percent, a 14.7 percent improvement.

4ESS Switch Sensitivity Study

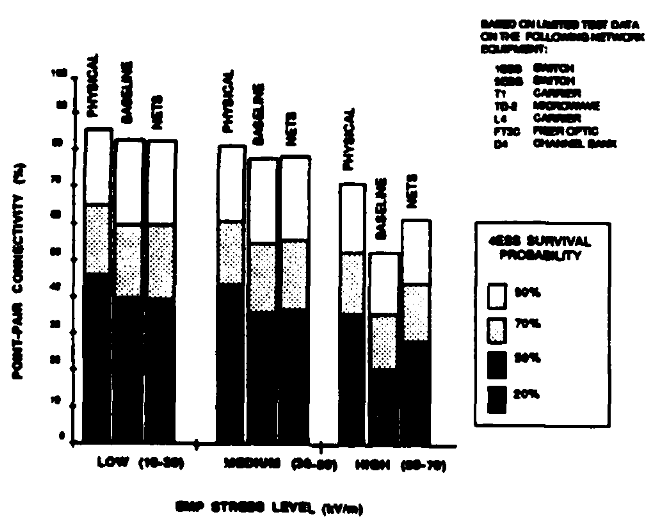
(U) In this sensitivity study the 4ESS switch was assumed to survive with the following probability values: 90, 70, 50 and 20 percent, at each of the three stress level ranges.

Exhibit ES-1
(U) Network Connectivity:
No Equipment Sensitivity Study



(U) The results of this 4ESS sensitivity study (Exhibit ES-2) illustrate that the performance of the 4ESS switch is extremely critical to the performance of the network. This is primarily due to the following three reasons:

EXHIBIT ES-2
(U) Network Connectivity:
4ESS Switch Sensitivity Study

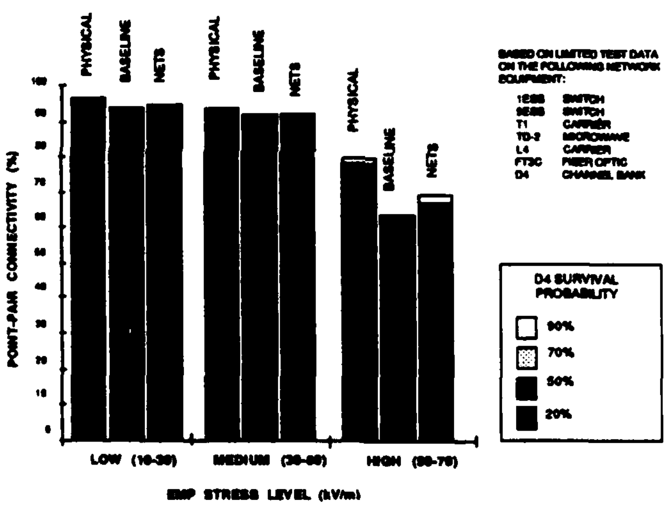


- Fifty percent of the toll network switches are 4ESS switches
- The NETS resources are located in 4ESS switches
- In general, 4ESS switches are highly interconnected, i.e. they contain many trunk lines.

D4 Channel Bank Connectivity

The results of the D4 channel bank sensitivity study are presented in Exhibit ES-3. Note that the connectivities are virtually the same for each D4 channel bank survivability, i.e. they overlap. Thus there is practically no degradation on network connectivity as the D4 survivability degrades from 90 to 20 percent for all three EMP stress levels. This is because there are so few analog switches, and that the network is still dominated by analog transmission facilities. These results are only applicable at the toll level.

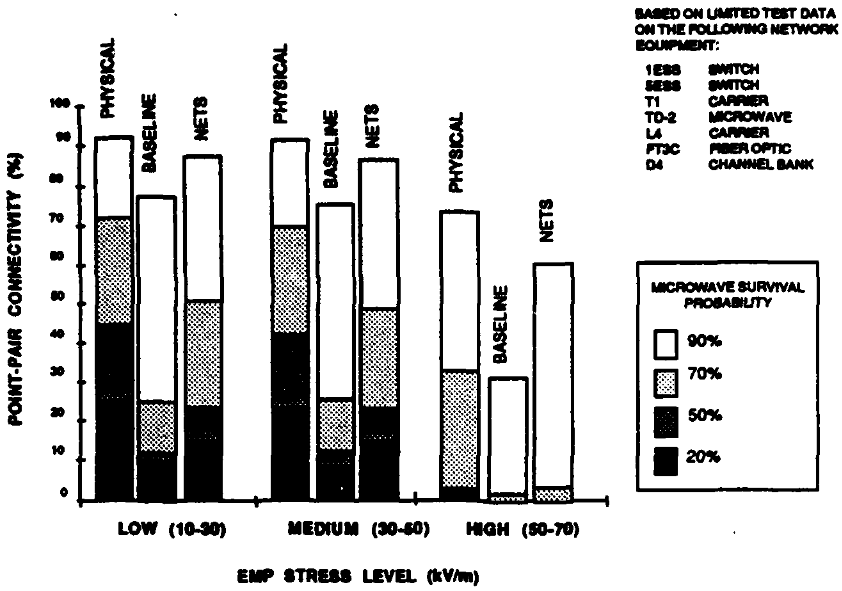
EXHIBIT ES-3
(U) Network Connectivity:
D4 Channel Bank Sensitivity Study



Microwave Sensitivity Study

(U) Exhibit ES-4 presents the results of the microwave transmission facility sensitivity study. The results indicate that network performance is extremely critical to the performance of network microwave systems. In all instances, the NETS connectivity is significantly higher than the PSN baseline connectivity. NETS improves connectivity at such a high rate because most of the switches, where NETS capabilities are stored, survive; and NETS makes greater use of the surviving transmission facilities.

EXHIBIT ES-4
(U) Network Connectivity:
Microwave Transmission Facility Sensitivity Study



(U) CONCLUSIONS

(U) As a result of this investigation the following recommendations are offered.

- EMP testing of the 4ESS switching system. This switch is the most prevalent switch in the AT&T toll network and is also the switch type presently envisioned to store many NETS capabilities. It is therefore of great importance to understand how the 4ESS switch responds to EMP exposure, as illustrated in the sensitivity study.

- EMP testing of a solid state microwave transmission facility. Analyses results indicate that network connectivity is closely correlated with the performance of its microwave transmission facilities. However, EMP test data is only available for an older vacuum tube based system while much of the network is comprised of solid state based microwave transmission facilities. It is therefore suggested that EMP testing of a solid state equipment, which is generally more susceptible to EMP degradation than a vacuum tube system, be conducted.

1.0 (U) INTRODUCTION

(U) The Officer of the Manager, National Communications System (OMNCS) has been tasked by Executive Order (E.O.) 12472 and National Security Decision Directive (NSDD) 97 to address Electromagnetic Pulse (EMP) effects on the National Security Emergency Preparedness (NSEP) telecommunication infrastructure. In support of this request the OMNCS has initiated, and manages, the EMP Mitigation Program. The major objective of this program is to identify, and where possible mitigate, EMP effects on the Public Switched Network (PSN) in direct support of the survivability and endurability objectives addressed by E.O. 12472 and NSDD-97. The program focuses on the PSN because National Communications System (NCS) member agencies rely on the PSN resources to fulfill most of their telecommunication requirements.

1.1 (U) BACKGROUND

(U) The EMP Mitigation Program uses a network level approach to assess EMP effects on network performance. The approach is twofold. First, the effects of EMP on network equipment are obtained. The OMNCS has made EMP test program results available on the 1ESS and 5ESS switches; the TD-2 microwave, L4 carrier, T1 carrier, and FT3C fiber optic transmission systems; and the D4 channel bank. Future OMNCS efforts call for EMP testing of the DMS-100 switch and possibly the 4ESS switch. Test program results are analyzed to quantitatively estimate the effects of EMP on the equipment. This set of equipment represents a significant, though not comprehensive, portion of the equipment types employed by the PSN.

(U) Second, the performance of the network exposed to EMP is characterized. This is accomplished by combining the equipment test program results with the network topology. A computer model, predicated on a statistical interpretation of EMP test data, processes this information and calculates a metric to characterize network performance. The model is run multiple times in a Monte Carlo process to probabilistically calculate the point-pair connectivity metric, which is a measure of the surviving connections with respect to the original connections. Previous analyses calculated Baran connectivity, a function of the largest "island" of connected switches. While this analysis calculates point-pair connectivity as it requires less computer processing resources. In interpreting the results of the network level analyses it is important to acknowledge fundamental uncertainties in the supporting input data.

(U) Previous work focussing on the network level approach to EMP effects analysis on the PSN and Nationwide Emergency Telecommunications Service (NETS) network, an enhancement to the PSN, can be found in references 1 and 2, respectively. The function of NETS is to provide additional routing capabilities for key government users with requirements for NSEP telecommunication capabilities. The enhanced routing is obtained by augmenting the current PSN call control mechanisms. NETS call controllers, which are placed at selected toll switches, provide additional connectivity for emergency calls by circumventing the normal PSN network routing tables. These analyses used the NETS Task 2 data base to statistically describe the network topology. The results provided estimates of the physical connectivity of networks exposed to EMP.

(U) In addition to the EMP effects analyses, current OMNCS activities address the network level effects of fallout radiation, an ancillary phenomena to EMP. The proposed approach, documented in reference 3, is similar to the network level EMP effects approach. The radiation portion of the program is in its initial phase of development; presently, no network level fallout radiation analyses have been performed.

1.2 (U) INVESTIGATION

This analysis has three main objectives:

- To evaluate the affect of the 4ESS switch, the D4 channel bank, and the microwave transmission facilities on network performance

- To develop an accurate network equipment data base for more comprehensive analyses

- To extend prior work on this subject into the areas of logical as well as physical connectivity.

All of these goals were attained during the course of this study.

(U) The analysis described in this report is a network level EMP effects sensitivity study on the 4ESS switch, the D4 channel bank, and the microwave transmission facilities. As a result of this analysis, the OMNCS will better appreciate the affect that each equipment type under study has on overall network performance.

(U) Three types of telecommunications equipment are evaluated in this sensitivity study: 4ESS switches, D4 channel banks, and microwave transmission facilities. The 4ESS switch is the most prevalent switch in the toll network. However, no test data exists to descibe its behavior in an EMP stressed environment. In lieu of test data on the 4ESS, present analyses assume that the 4ESS responds equivalently to the 5ESS. Appropriately, the 4ESS is an evaluated piece of equipment in this sensitivity study.

(U) Even as the importance of the D4 channel bank, an analog/digital interface, decreases as the network migrates digitally, it is still considered a critical PSN equipment type for the foreseeable future. Applicable test data on the D4 channel bank is minimal which, like the 4ESS, makes it difficult to statistically characterize its response to EMP. Therefore, the D4 channel bank is also addressed in this analysis.

(U) Microwave transmission facilities are selected for the sensitivity study because (1) they are widely used within the network and (2) the test data is only available on an older analog vacuum tube type system. More recent microwave systems employ solid state technology that is generally perceived to be more vulnerable to EMP damage.

(U) This analysis addresses both physical and logical connectivity. Two switches are physically connected as long as they are connected directly, or indirectly through intermediate switches. Switches are logically connected as long as they are physically connected <u>and</u> as long as the network has the capability to support communications over those physically connected assets. Two logical connectivity metrics are calculated: the PSN baseline connectivity and the maximum commercial carrier connectivity. The PSN baseline connectivity represents the actual routes typically used by the commercial carrier to connect two end users. The maximum commerical carrier connectivity, henceforth often referred to as NETS connectivity, represents all of the channel group connections made possible or avialable by the commercial carrier (AT&T) but which are not typically used primarily because of economic considerations. Enhancements provided by NETS are designed to improve the PSN baseline connectivity ultimately to the maximum commercial carrier connectivity performance level by supporting additional routing capabilities.

(U) The network addressed in this EMP effects analysis is the toll portion of the post-divestiture AT&T network. This network represents an accurate and current description of a major portion of the PSN. The network description has been provided to the OMNCS as part of the NETS Task 3 effort. The following information is specified in the data base:

- Switch types
- Switch locations
- Switch interconnections
- Transmission facility types
- Transmission facility locations.

This data base is the most comprehensive one to date, and has been extensively studied and processed to support detailed analytical analyses. The present understanding of the network is markedly improved over that in the previous network level EMP analyses which focused solely on a statistically simulated network. Further, this improvement leads to greater confidence in the analysis data. As a result of this investigation, the network connectivity measure represents a more accurate value for network performance.

(U) The results obtained in this investigation were studied to test the following propositions related to the performance of the AT&T toll network in an EMP stressed environment:

- The variation in survival probability of 4ESS switches, microwave transmission facilities, and D4 channel banks could significantly affect the overall performance of the public switched network

- The PSN baseline connectivity measure reflects an appreciable loss in percentage connectivity from the physical connectivity measure

- NETS could significantly enhance the performance of the PSN with its powerful routing system capabilities.

The results of these propositions to the observed data are presented in section 5.0 and reviewed in section 6.0.

1.3 (U) ORGANIZATION

(U) This report is composed of six sections. First, section 2.0 addresses the network analyzed in this study. Also provided in this section is an explanation of how the data base is interpreted and processed, along with background information on network switches, transmission facilities, physical connectivity and logical connectivity.

(U) Section 3.0 describes the Network Connectivity Analysis Model (NCAM). This model integrates equipment test results with the network topology to calculate the performance of EMP exposed networks; and forms the basis for the network level approach. The model quantifies network performance by calculating the point-pair connectivity metric. In addition NCAM assesses connectivity from both a physical and logical perspective.

(U) Section 4.0 addresses the equipment test data. Included is the processed EMP test results on the 1ESS and 5ESS switching systems; the TD-2 microwave, L4 carrier, T1 carrier, and FT3C fiber optic transmission facilities; and the D4 channel bank. Background information and any applicable assumptions with regard to the testing procedures are provided for all seven equipment testing programs.

(U) Section 5.0 presents the results of this study and addresses the manner in which the sensitivity study was performed on the 4ESS switch, the D4 channel bank, and the microwave transmission facilities. The results illustrate how sensitive network performance is to variations in the survivability of these three equipment types. By comparing the PSN baseline connectivity with the maximum commercial connectivity, the improved connectivity provided by NETS can be quantitatively evaluated.

(U) Section 6.0 summarizes the major findings of these analyses. This section is concluded with suggestions for future investigation, including recommendations for future EMP testing.

2.0 (U) NETWORK TOPOLOGY DESCRIPTION

(U) The OMNCS network data base of telecommunications assets was used in the assessment of EMP effects on network performance. This data base, obtained by the OMNCS as part of the NETS Task 3 effort, contains complete information on the AT&T network transmission and switching facilities as of January 1986. This section describes the AT&T Toll network portion of the OMNCS data base and the steps taken to analyze the logical and physical connectivity of the network in an EMP stressed environment.

2.1 (U) DATA BASE DESCRIPTION

(U) The AT&T toll network portion of the OMNCS data base is composed of three principal files: the switch file, the physical transmission file, and the logical transmission file. Each file describes a specific element of the AT&T network. Below is a description of these files along with summary tables of transmission facility and switch types.

2.1.1 (U) Switch File

(U) The switch file determines the types and locations of switches throughout the AT&T network. A list of the AT&T switch types, and the location of each of the network's 344 switches, is included in this file. The file contains an 11-character Common Language Location Identifier (CLLI) code that specifies the switch class, the switch type and the vertical and horizontal coordinates of the switch. The following exhibit, generated from the AT&T network portion of the OMNCS data base, is a summary of the types and quantities of switches in the network.

EXHIBIT 2-1

(U) Switch Types and Quantities

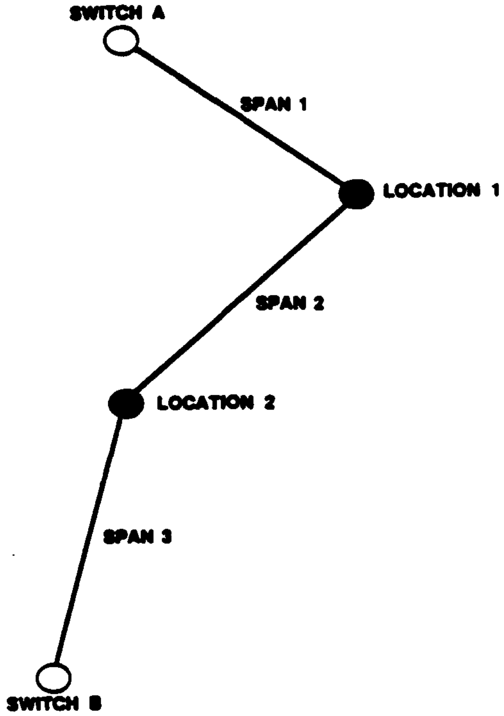
Switch Type	Manufacturer	Quantity
1ESS	AT&T Technologies	31
4ESS	AT&T Technologies	104
5ESS	AT&T Technologies	29
DMS-200	Northern Telecom	19
DMS-100/200	Northern Telecom	1
EAX3	Automatic Electric (GTE)	3
EAX5	Automatic Electric (GTE)	3
DCO200	Stromberg Carlson	1
Unknown Toll		20
Unknown End Office		133

2.1.2 (U) Transmission Facility Files

(U) Transmission facilities are the physical media that support telephony communications within the network. A transmission facility is based on one of many technologies, such as fiber optics, analog microwave, etc. The AT&T data base refers to a transmission facility as a span. The transmission facility file is an array of span records, where each span record specifies the state, city, building, switch identifier and toll status of the two span endpoints. The information on each span endpoint is contained in a CLLI code. Span endpoints may be switches, repeaters, or other types of transmission facility junction points. For example, in Exhibit 2-2, a connection between hypothetical switches A and B with two repeaters might contain three spans: one between switch A and location 1, one between location 2 and switch B, and one between the two location points. This array of span information is referred to as the physical transmission facility file.

EXHIBIT 2-2

(U) Illustration of Network Spans



(U) Based on the physical transmission file, a logical transmission file is derived by data base processing. The logical transmission file specifies the logical connections between the switches in the network. This network performance analysis uses the AT&T term Originating Route Identification Numbers (ORINs) in its analysis of logical connectivity. An ORIN, composed of multiple spans, is an analog or digital transmission media that supports communications between switches. It is noteworthy that the communications path is generally chosen by the commercial carrier on predominantly an economic basis. Using ORINs, the two switches are said to communicate from a logical perspective; hence logical routes are composed of ORIN connections.

(U) The ORIN information includes a pointer to the first span in a sequence of spans. This sequence of spans describes a physical route for the ORIN between the switch endpoints, the types of switching functions at the end points, and the airline miles between these switches. An ORIN can contain a variety of transmission media but will generally operate as either all digital or all analog. For example, a digital ORIN may start out as a T-carrier, transition to digital microwave, and then finish with a fiber optic system.

(U) Exhibit 2-3, also generated from the data base, summarizes the transmission facility types and the corresponding percentages of these facilities which exist in the network.

EXHIBIT 2-3

(U) Transmission Facility Types and Percentages

Transmission Facility Types	Percentage (%) of network
Digital T Carrier	18.9%
Analog L Carrier	12.0%
Analog Microwave	59.0%
Digital Microwave	5.6%
Analog N Carrier	1.6%
Fiber Optic	2.7%
Satellite	0.2%

2.2 (U) NETWORK CONNECTIVITY

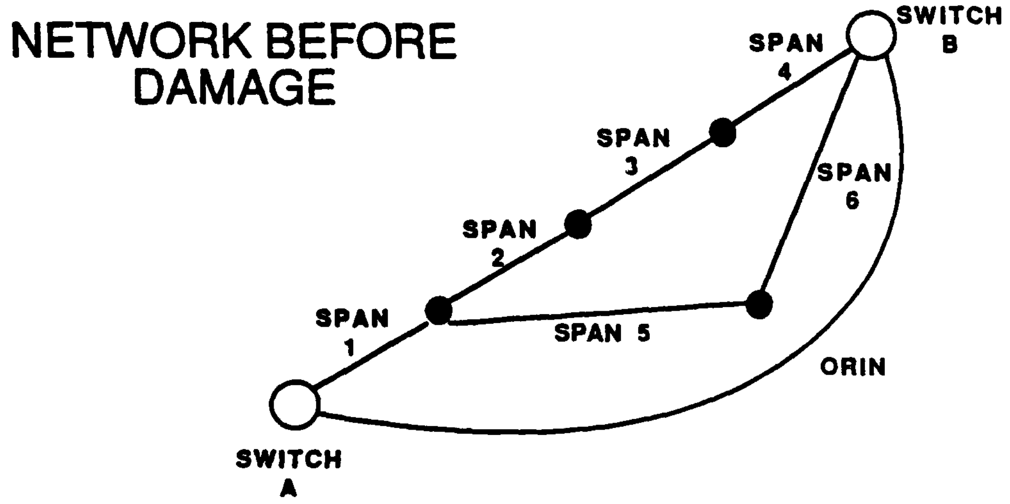
(U) This analysis addresses both physical and logical connectivity of the network. Physical connectivity assesses the survivability of the physical assets of the network. In the physical connectivity analysis, one switch is physically connected with any other as long as there is an existing path between the pair of switches. Moreover, the network is physically connected when switches can communicate directly, or indirectly through intermediate switches via any existing set of spans.

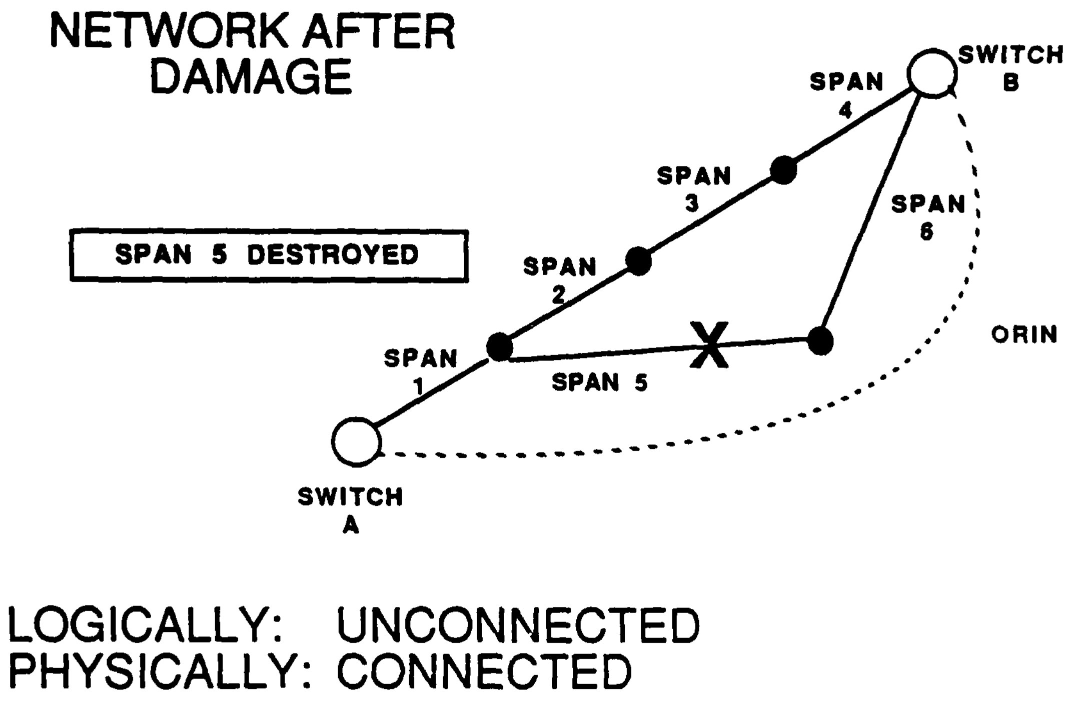
(U) Logical connectivity is based on the set of ORINs which describe the available spans between switches. The shortest path between these switches, termed least cost, generally determines the manner in which the ORINs are joined together and consequently, how each switch communicates with other switches. Therefore, if an ORIN or group of ORINs does not exist between two switches, the network cannot support communications between the two switches. A logical connectivity analysis first assesses ORIN connectedness and then determines the surviving logical routes. Logical routes over the physical paths between switch pairs are determined by a predefined set of ORINs. A logically connected path exists as long as an ORIN with surviving spans is available. Although additional physical connections may exist, only those spans included in the ORIN list are considered in a logical connectivity assessment. Therefore, physical and logical connectivity are equivalent if and only if the set of ORINs is an exhaustive list of the physical routes. ORIN connectivity equals the maximum commercial carrier connectivity and is representative of the service NETS can provide.

(U) The simple network in Exhibit 2-4 illustrates the distinction between physical and logical connectivity. The first network shows the connections before damage. Two physical paths exist between switches A and B: the first path transverses spans 1 through 4 and the second path uses spans 1, 5 and 6. Only one logical path, indicated by the ORIN composed of spans 1, 5 and 6, exists between these switches. After the network has been damaged, span 5 is destroyed. An "X" implies that the network element has been destroyed. The first physical path between the switches, that is, the path that traverses spans 1 through 4, remains intact and physical connectivity is retained. The single logical connection over the ORIN, however, has been destroyed. Therefore, the network is not logically connected.

EXHIBIT 2-4

(U) Physical Versus Logical Connectivity





(U) The network presented in this exhibit is highly simplified. In the actual PSN there is not an ORIN between each pair of switches. In such cases the network concatenates a predefined set of ORINs together to attain a logical connection.

3.0 (U) SIMULATION OF NETWORK PERFORMANCE

(U) This section describes the computer modelling used to estimate the effects of EMP on network physical and logical connectivity. The model measures network performance by the point-pair connectivity metric, which is a measure of the post-attack connections versus pre-attack connections. Previous network level analyses focussed only on physical connectivity, and quantified network performance with the Baran metric. Baran connectivity is a function of the percentage of switches that both survive and remain connected to the largest "island" of switches following an EMP attack. However, point-pair connectivity is more tractable to calculate for logical analyses and hence is the selected metric for this analysis.

3.1 (U) INTRODUCTION

(U) The computer model has three tasks to perform. First, it must generate a network topology consisting of the switches and transmission facilities that comprise the post-divestiture AT&T toll portion of the PSN. The model identifies the number, location and type of switches and transmission media as specified in the NETS Task 3 data base. This is a significant improvement over previous network level EMP efforts which used a simulated network.

(U) The second function of the model is to determine which elements of the network survive a disturbance. This analysis assumes the disturbance to be an EMP stress. An element has "survived" if it is fully or partially operable after exposure to an EMP stress level. Temporary upset, where an equipment fails for a duration of time is not addressed. For each element (switch or transmission facility), an EMP-induced survival probability is selected for the particular EMP stress level under study. A point estimate of the survival probability is sampled from this distribution and a pseudorandom test is performed on each element of the network to determine whether or not it survives the EMP stress.

(U) The third task is to calculate the point-pair connectivity metric following the simulated EMP disturbance. Both physical and logical point-pair connectivity (PSN baseline and NETS), discussed in section 2.0, are calculated by the model.

(U) These three tasks are replicated many times and are always based on the same statistical and probabilistic input data. This approach is known as the Monte Carlo procedure. For each replication in the Monte Carlo procedure, the point-pair connectivity metric is computed. At the conclusion of the Monte Carlo process, two primary statistics are calculated, the mean and the standard deviation of the discrete point-pair connectivities. The standard deviation provides insight into the amount of dispersion that is expected among different replications within the same Monte Carlo procedure. Histograms of the replication results can be produced to illustrate the standard deviation.

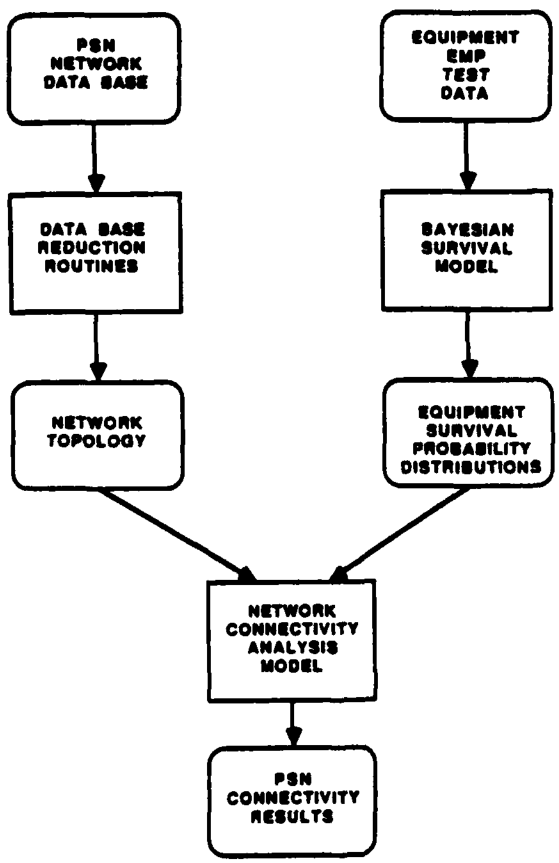
3.2 (U) NETWORK LEVEL COMPUTER MODELING

(U) Effects of EMP on the post-divestiture AT&T toll network are actually assessed using two computer models: the Bayesian Survivability Model (BSM) and the Network Connectivity Analysis Model (NCAM). The BSM is used to estimate the EMP-induced survival probabilities of elements (switches and transmission facilities) in the network.

The results of EMP tests on various network element types are the primary input data of the BSM. The outputs of the BSM are then input to NCAM -- a model designed to estimate physical and logical connectivity among network switches under different EMP stress levels. The functional flow of this approach is shown in Exhibit 3-1. In the subsections that follow, detailed discussions of the two models are presented.

EXHIBIT 3-1

(U) Network Level EMP Effects Analysis: Functional Flow Diagram

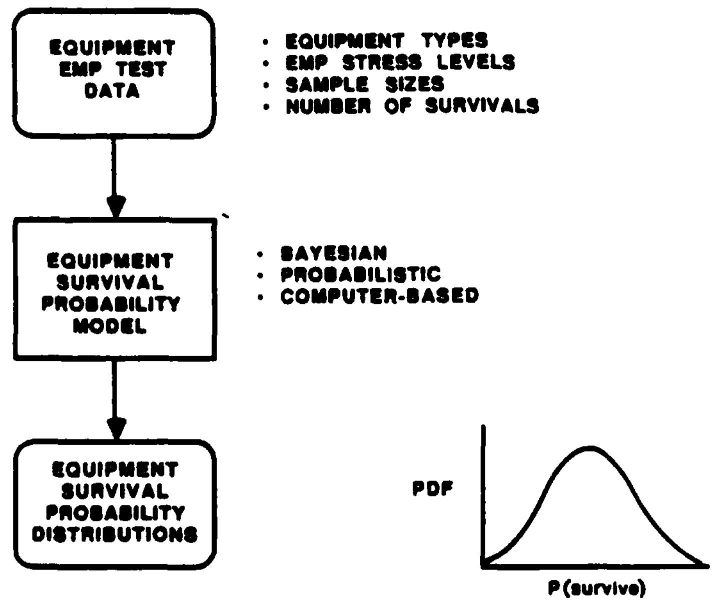


3.2.1 (U) Bayesian Equipment Survivability Model

(U) This model is a computer-based application predicated on Bayesian statistical theory. It is designed to characterize the EMP-induced survival probabilities for different types of telecommunications equipment (network elements). The full mathematical explanation of this approach is available in reference 4. Exhibit 3-2 illustrates the flow of BSM. Results from EMP tests on network elements are input to the model. Using a computer, a numerical approximation of the Cumulative Distribution Function (CDF) of survival probability from the Beta posterior distribution is calculated. The beta posterior distribution is obtained by performing a Bayesian process on an assumed noninformative prior distribution and the equipment EMP test data. Using this approach for applications such as EMP test data, is suggested and supported in reference 5.

EXHIBIT 3-2

(U) Bayesian Survivability Model: Functional Flow Diagram



(U) The numerical approximations are used to characterize CDF curves that describe the probability of element survivability. For each tested element, a unique CDF curve is developed for the EMP stress levels: low, medium and high. These levels are arbitrary categorizations of discrete electric field strengths at which the equipment has been tested. This classification is necessary because not all equipment has been tested at the same discrete EMP stress levels. The results of the equipment survivability model are subsequently used as inputs to the NCAM.

3.2.1.1 (U) Bayesian Model Inputs. EMP test data are the sole inputs of the equipment survivability model. The data used in this analysis were collected during multiple tests of telecommunications equipment over a range of EMP stress levels. Exhibit 3-3 illustrates a hypothetical example of data for an arbitrary element type.

EXHIBIT 3-3

(U) Hypothetical Example of EMP Test Results for a Specific Network Element

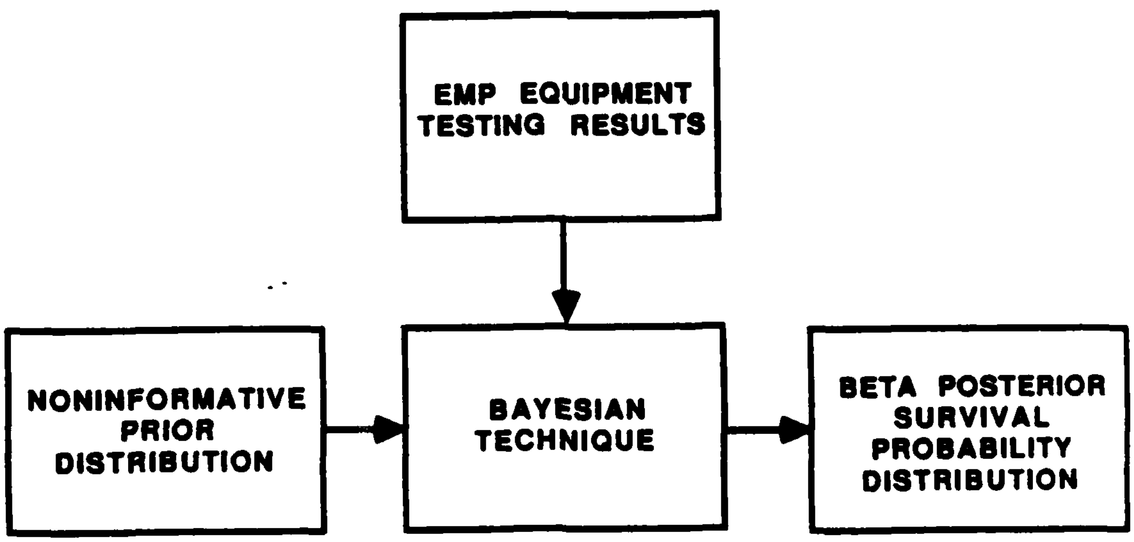
EMP Stress Level:	Low	Medium	High
# of Tests:	9	6	7
# of Survivals:	8	4	4

(U) Exhibit 3-3 specifies that the element was exposed to a low EMP stress level and survived eight out of the nine trials. When exposed to a medium level, the element survived four of six trials. When exposed to the high EMP level seven times, the element survived four times. For each element tested, data were assembled into a similar format.

3.2.1.2 (U) Bayesian Modeling Implementation. Based on EMP tests, the variable "p" is defined as the fraction of elements of a given type that survive a specified EMP level. The calculation of the posterior probability distribution of p is then calculated and used in the network level EMP effects analysis. The calculation is made using the Bayesian statistical approach. This approach blends the knowledge gained from an experimental process (test data) with assumed prior knowledge (a prior distribution for p), to develop posterior knowledge (a posterior distribution for p). In this analysis, the assumed prior distribution is a noninformative prior distribution and the generated posterior distribution is a Beta distribution. Exhibit 3-4 illustrates this approach.

EXHIBIT 3-4

(U) The Bayesian Statistical Approach



(U) The concept of Bernoulli trials is applied when there are only two possible outcomes to a trial (e.g., when tossing a coin there are only two possible occurrences, heads or tails). Since this analysis is only concerned with whether an element survives or fails at a particular EMP stress level, it is appropriate to use the binomial distribution for the number of element survivals out of n experimental trials. The average value of p would be expected to be quite high for well-designed EMP-hardened equipment.

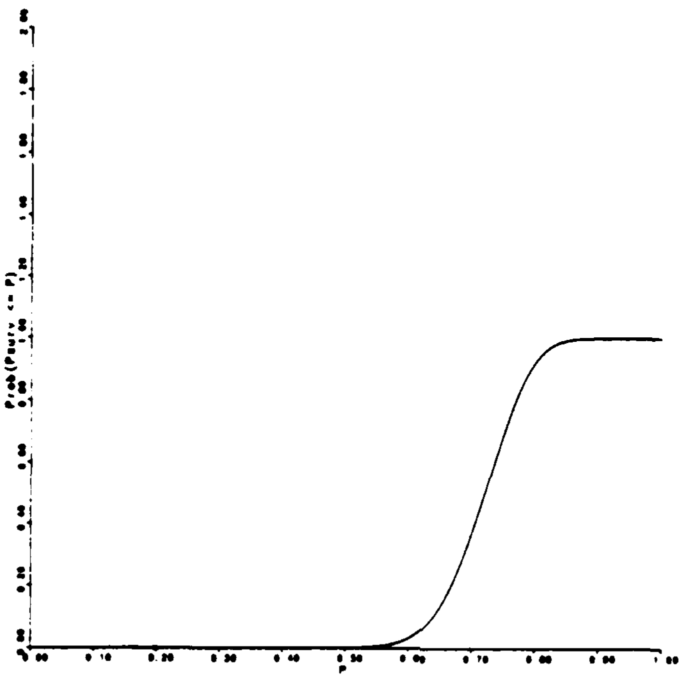
(U) When Bayesian techniques are applied to the noninformative prior distribution and the Bernoulli trial outcomes, the obtained posterior Probability Density Function (PDF) for p (the element survival rate) is the continuous Beta distribution, as explained in reference 4. Finally, the required CDFs, which characterize the survival probabilities of network elements, are calculated via the numerical approximation of the incomplete Beta function. The numerical approximation, which is called the incomplete Beta function, is described in reference 6. The BSM is run for each element type at a discrete EMP stress level. Exhibit 3-5 illustrates an example of a generated CDF output from the BSM using hypothetical test data for an equipment that survived 39 of 54 exposures.

3.2.2 (U) Network Connectivity Analysis Model (NCAM)

(U) Network performance is measured in this analysis by the point-pair approach. In this analysis, the term connectivity may imply physical or logical connections between switches. The physical connections may be either direct connections between the switches, or a set of connections which form a path between the switches. Physical connectivity means that there is a path between a pair of switches, while logical connectivity implies the

EXHIBIT 3-5

(U) CDF of the Bayesian Survivability Model:
Hypothetical Example -- 39 survivals/54 exposures

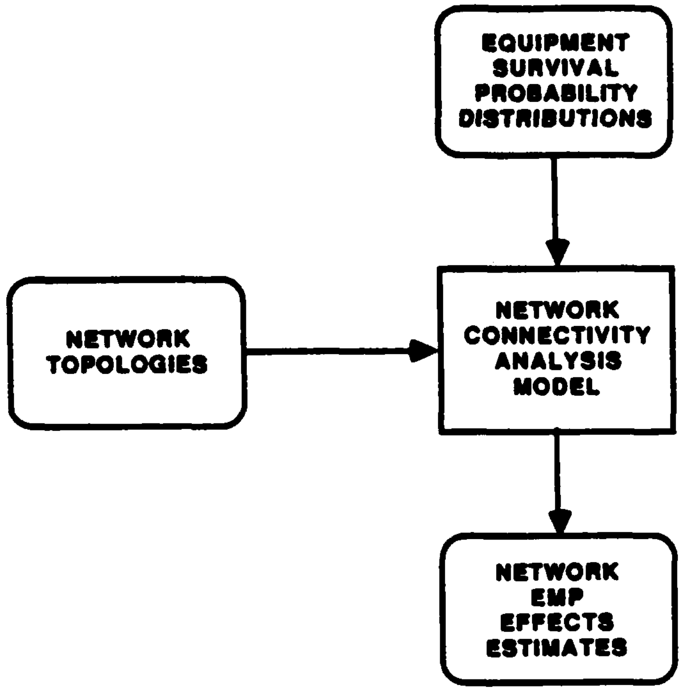


existance of a physical path as well as the network capability of routing traffic over that path. Exhibit 3-6 summarizes the functional flow diagram associated with the point-pair connectivity metric. Network topology and probabilistic information on equipment survival rates when exposed to simulated EMP stress levels are the model inputs. These inputs are processed by NCAM to estimate the effects of EMP on the connectivity of the original network.

(U) This analysis uses the AT&T concept of ORINs to assess logical connectivity. An ORIN, as defined in section 2.0, is the set of physical resources over which two switches may communicate. An ORIN survives as long as all of its physical resources survive. Two switches are deemed logically connected in the PSN baseline so long as there is a path of three or less ORINs between them. They are deemed logically connected in the NETS network if there is a path of twelve or less ORINs between them.

EXHIBIT 3-6

(U) Network Connectivity Analysis Model:
Functional Flow Diagram



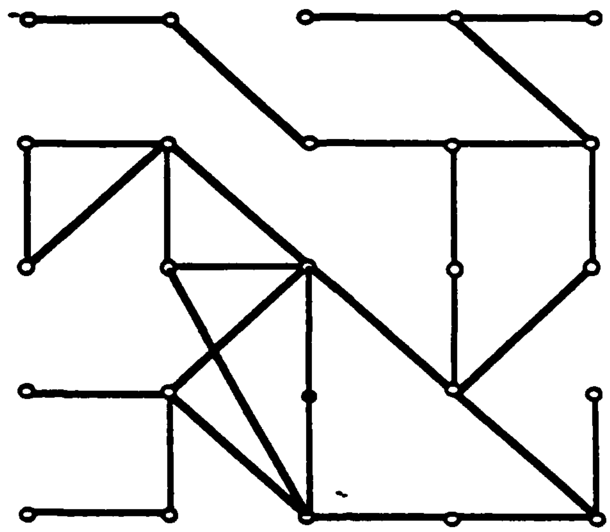
(U) An illustration of the point-pair approach is given in Exhibit 3-7. The top figure shows a hypothetical network topology. All of the switches and transmission facilities are equal, which means the network is "unweighted." The network has 100-percent physical point-pair connectivity because each switch has at least one physical path to all other switches. As the network has 25 switches, and each switch can reach the 24 other switches, there are a total of 600 connections.

(U) Following a hypothetical disturbance (e.g., a HEMP attack), some elements may become inoperable. The bottom figure depicts a network resulting from such a disturbance. An "X" is placed through elements that fail to survive the disturbance. The point-pair connectivity is calculated with the following equation:

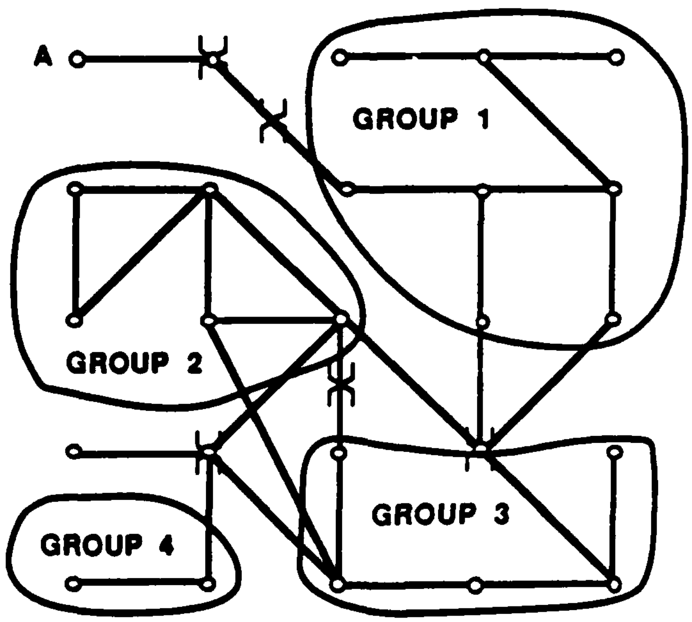
EXHIBIT 3-7

(U) Point-pair Network Analysis Approach: Illustrative Example

PRE-ATTACK - 100% CONNECTIVITY



POST-ATTACK - 16% POINT-PAIR CONNECTIVITY



X: DESTROYED

$$\text{point-pair connectivity} = \frac{\sum_{i=1}^{\text{number of islands}} n_i\,(n_i - 1)}{N\,(N - 1)}$$

where i = island under study (must be larger than 1 switch)

n = number of switches in island i

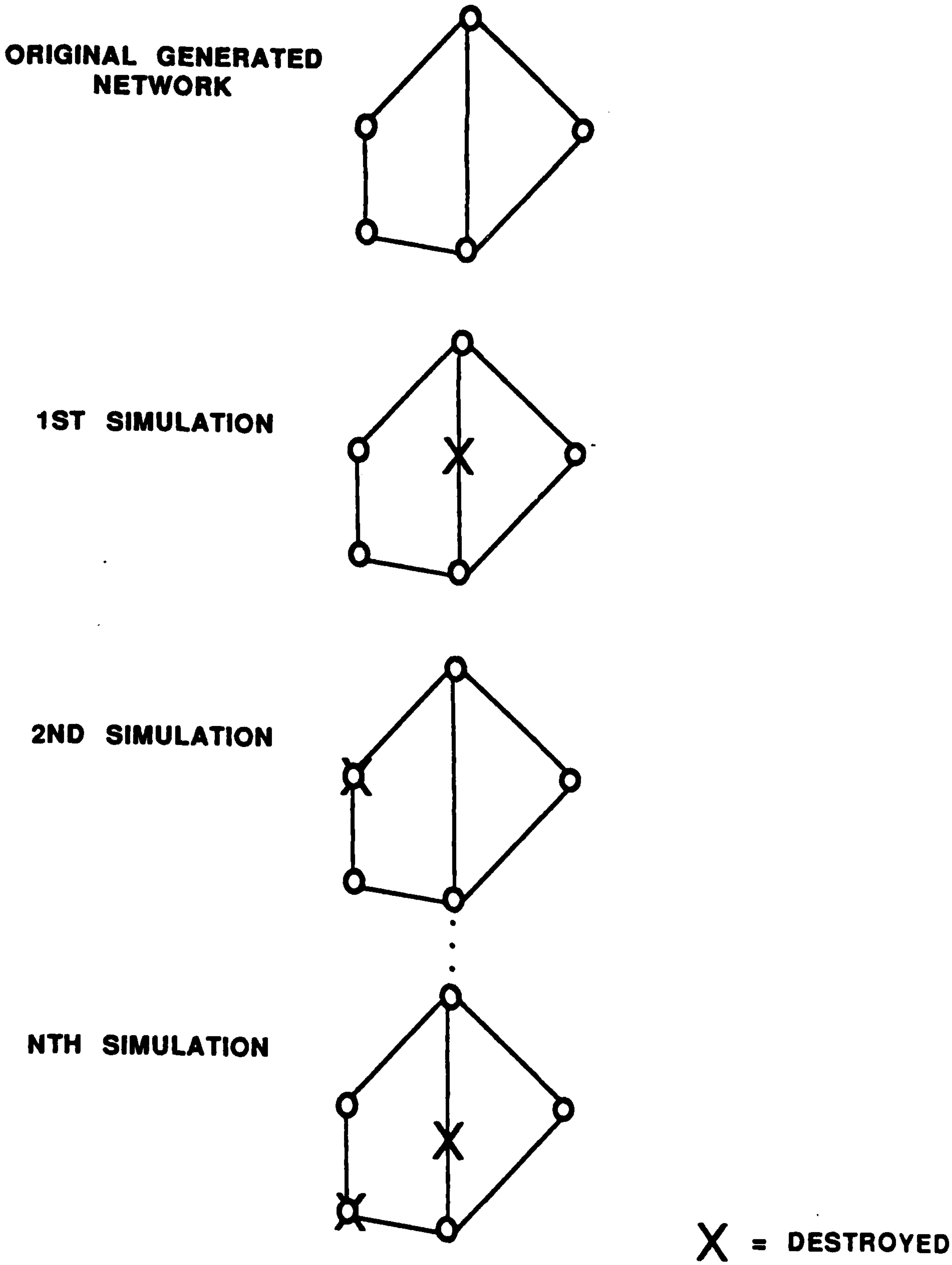
N = number of switches in the original network under study

The physical point-pair connectivity is recorded as approximately 16 percent, as 98 of the original 600 connections are maintained. A similar approach is employed to determine PSN baseline and NETS connectivity.

3.2.2.1 (U) NCAM Model Inputs. The computer-based Network Connectivity Analysis Model requires two inputs: network topology information and EMP-induced equipment survival probability distributions. Processing this information and performing multiple Monte Carlo simulations yields the point-pair network performance metric. This connectivity metric assesses the telecommunications capabilities of an EMP-exposed network. An example of the Monte Carlo procedure is provided in Exhibit 3-8. As shown, multiple tests are performed on the network. Each network element is assigned a random survivability value selected for the particular EMP stress level under study. This value is compared to another survivability value sampled from the tested element's CDF curve. The element survives if the sampled value is larger than the assigned value. Each element's survivability for one simulation is independent of its survivability for another simulation, meaning different equipment may fail in different simulations.

EXHIBIT 3-8

(U) Monte Carlo Procedure



(U) For this analysis, an actual network topology is generated from data on the AT&T Communications toll network data base. The network consists of PSN switches and transmission facilities. Two examples of switches may be the 4ESS and 5XB switching systems. Microwave links and copper wire cables are examples of typical transmission facilities. A detailed discussion on the AT&T network data and the network topology is presented in section 2.0 and reference 7.

(U) The second set of inputs to the model consists of the EMP-induced equipment survival probability distributions obtained from the BSM. These probability distributions are calculated for each type of telecommunications equipment at each EMP stress level for which test data are available. Equipment that have not been EMP-tested are assigned the survival probability distributions of the most technologically similar equipment which has been tested. For example, the 4ESS switch may adopt the CDF of the tested 5ESS switch because both are digital switches manufactured by AT&T Technologies. Using one element's distribution curve in place of another element's CDF induces an unquantified error in the network level results. This error can be partially addressed by performing sensitivity studies on the untested equipment.

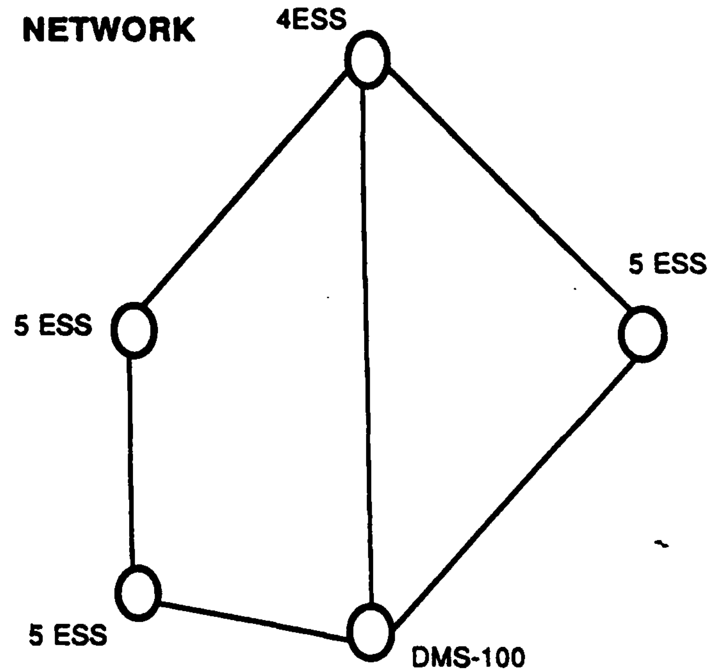
3.3 (U) SENSITIVITY ANALYSIS

(U) An additional study is performed to determine the sensitivity of network connectivity (physical and logical) to the behavior of a particular element in the network. This analysis is generally conducted when little or no data are available describing the behavior of a network element exposed to EMP. The procedure for the analysis is as follows. First, the element addressed in the sensitivity study, depicted in Exhibit 3-9, is assigned a range of

EXHIBIT 3-9

(U) Sensitivity Analysis: Illustrative Example

ORIGINAL GENERATED NETWORK



CONNECTIVITY CHART

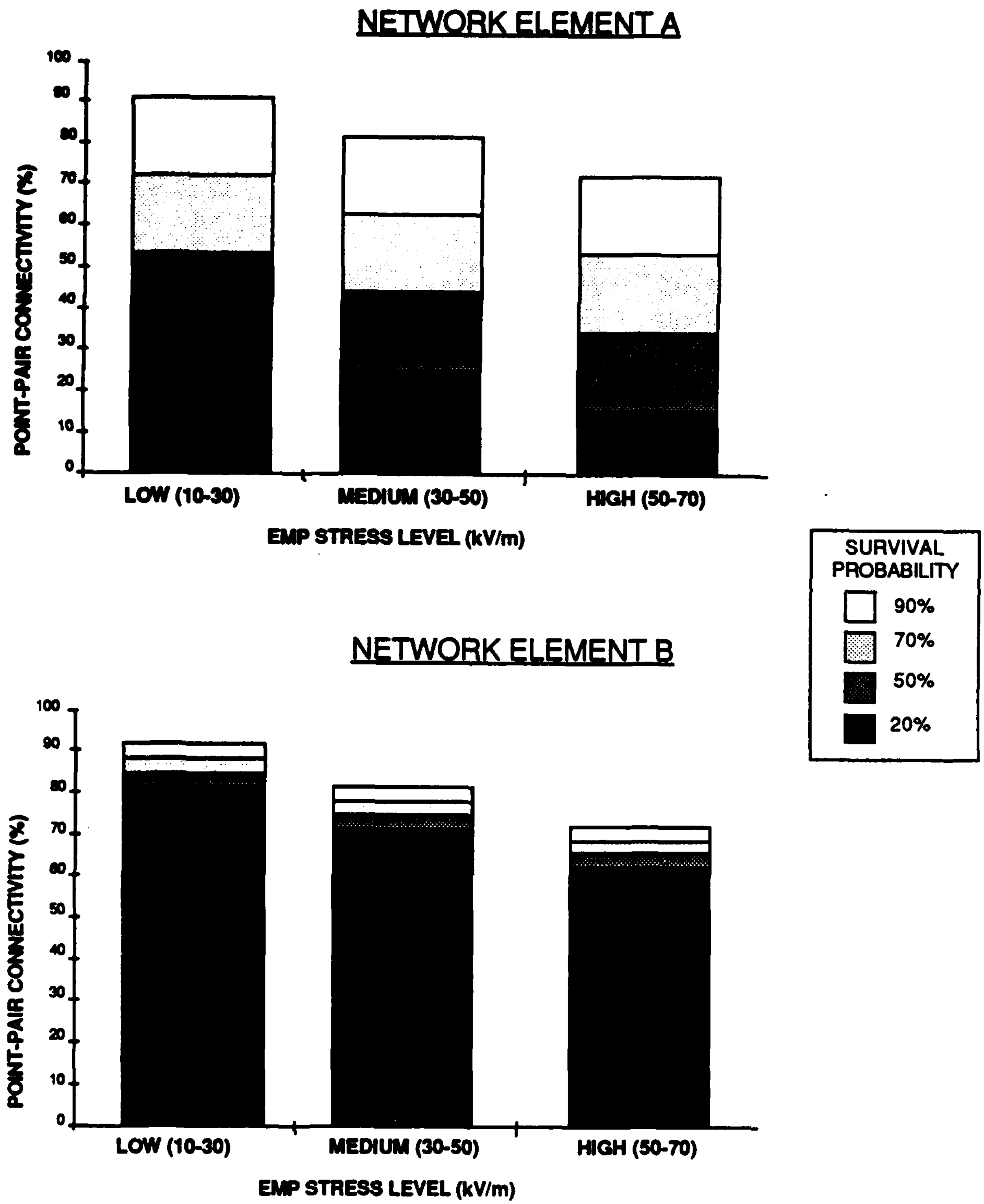
NETWORK ELEMENT SURVIVABILITY	EMP STRESS LEVEL		
4ESS	LOW	MED	HIGH
.95	MEAN / STD. DEV.		
.90			
.80			
.75			
.50			
.25			

discrete survivability values where each value describes the probability that the element survives an EMP stress level. For example, the 4ESS switch element may be assigned survivability data as shown in the connectivity chart of Exhibit 3-9. Second, the BSM determines which of the remaining elements survive the EMP stress level. Third, the network point-pair connectivity for the simulated stress level is calculated. After the Monte Carlo procedure, the mean and standard deviation of the network connectivity are calculated for the three stress levels: low, medium and high.

(U) The network level sensitivity study is a tool used to assess survivability assumptions. The degree of sensitivity of the network connectivity to the element under study is useful when determining key communications facilities in a network. In particular, the error produced when using one element's CDF for another element's CDF may be further qualified. Consider, for example, that elements A and B in Exhibit 3-10 are untested switches and therefore have no survivability data. Quantifiably, their value to the overall performance of the network may be expressed. The graphs show that when the likelihood that element A will fail increases, the entire network's performance decreases. In contrast, as element B's probability for survival decreases, network performance remains relatively unaffected. This is illustrated by the fact that, in the element A plot, the bars are more "spread out" than they are in the element B plot. This indicates that element A is more critical to network connectivity than element B. Therefore, testing of element A should have greater precedence than testing of element B.

EXHIBIT 3-10

(U) Sensitivity Analysis Application



Certain Portions of Section 4.0

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<u>UNCLASSIFIED</u>

4.0 (U) EMP EQUIPMENT TEST DATA

(U) The OMNCS has EMP test data on selected PSN telecommunications equipment types. Such data is available for the following set of equipment:

- 1ESS switching system
- 5ESS switching system
- T1 carrier transmission system
- TD-2 microwave transmission system
- L4 carrier transmission system
- FT3C fiber optic transmission system
- D4 channel bank.

This data set, which includes a wide array of technology types, is a representivie portion of the equipment types employed in the PSN. The technology types covered include analog and digital switches, analog and digital (including fiber optic) transmission facilities, and ancillary equipment. This data is the basis by which network equipment survivability is addressed in the Bayesian Survivability Model (section 2.0).

(U) Due to the large number of equipment types in the network, it is economically prohibitive to EMP test each PSN equipment type. For equipment types that do not have EMP test data, this analysis assumes their survivability corresponds to the survivability of the most technology similar equipment for which data is available. For example, since the only microwave equipment tested was the TD-2 system, all microwave transmission facilities are assigned the survivability of the TD-2 system. This induces an inherent error in the network level results. As the OMNCS obtains more equipment EMP test data, the magnitude of this error will be reduced.

(U) The EMP test data come from two sources. The first is OMNCS sponsored testing programs which were conducted to support the network level EMP approach. The second is from other government sponsored testing programs (non-OMNCS) that were supported for their individual purposes. The results of the seven testing programs are summarized in reference 8.

(U) The network level EMP approach requires that equipment be viewed consistently. Therefore interpolation of the test data is necessary as the tests were conducted on different equipment, for different purposes, and under different conditions. This interpolation leads to a uniform approach to assessing all the equipment EMP test data.

(U) The interpolated results are presented in this section. First network switches are addressed, followed by transmission facilities, and then ancillary equipment. The results describe how the equipment respond to the EMP stress level categories of low, medium, and high. These three levels correspond to EMP field strength "bins" of 10-30 kV/m, 30-50 kV/m, and 50-70 kV/m. Based on the interpolated results, equipment survivability curves are developed with the Bayesian model described in Section 3.0. Three discrete curves are developed for each equipment tested, these curves represent equipment survivability at the three EMP stress level bins. Also addressed in this section is the rationale for assigning survivability curves for equipment types that have not been EMP tested.

4.1 EMP SWITCH DATA

(U) To date, two switches have been EMP tested. They are the 1ESS switch and the 5ESS switch -- both electronic switches manufactured by AT&T Technologies. The network analyzed in this report, which is comprised of 344 switches, contains eight switch types. The interpreted breakdown from the data base of these 344 switches is provided in Exhibit 4-1. Due to a lack of comprehensive test data, this analysis assumes all digital switches survive according to the 5ESS switch and all analog switches survive according to the 1ESS switch.

(U) Unknown switches which are at the toll level are assigned the survivability of the 5ESS switch, as toll switches are primarily digital. Unknown end-office switches are assigned the survivability of the analog 1ESS switch.

EXHIBIT 4-1
(U) Network Switch Survivability Assignment

SWITCH ACRONYM	TECHNOLOGY	MANUFACTURER
1AESS	ANALOG	AT&T TECHNOLOGIES
4ESS	DIGITAL	AT&T TECHNOLOGIES
5ESS	DIGITAL	AT&T TECHNOLOGIES
DMS-200	DIGITAL	NORTHERN TELECOM
DMS-100/200	DIGITAL	NORTHERN TELECOM
DCO200	DIGITAL	STROMBERG-CARLSON
EAX-3	DIGITAL	AUTOMATIC-ELECTRIC
EAX-5	DIGITAL	AUTOMATIC-ELECTRIC
UNKNOWN	UNKNOWN	UNKNOWN

4.1.1 (U) 1ESS Switch

(U) The 1ESS was the Bell System's first electronic switch. It was designed to serve urban areas where the demand for sophisticated applications was highest. EMP testing of the 1ESS switching equipment was conducted in 1968 on a complete AUTOVON 1ESS switch at Fort Apache Junction, Arizona. Documentation on the tests are available in reference 9. The tests measure the switching system response to simulated EMP stress levels that equaled or exceeded an assumed threat level.

(U) Both the 1AESS switch and the unknown end office switches are assigned survival curves based on the 1ESS switch as they are all analog switches. This is a valid assumption for the 1AESS as both are from the same AT&T Technologies switch family. It is done with the end office switches because it is believed that the local level still contains a high proportion of analog switches.

4.1.2 (U) 5ESS Switch

(U) In 1982 the digital 5ESS switch was introduced to replace existing electromechanical switches on a evolutionary basis. The modularity of the switch makes it appropriate for rural, suburban, and urban environments. The OMNCS sponsored EMP testing of the AT&T Technologies 5ESS switching system in 1986. These tests were conducted at the Air Force Weapons Laboratory EMP facilities on Kirtland Air Force Base in Albuquerque, New Mexico. Two simulators were used in the test -- the ALECS simulator generated pulses with vertical field strengths between 5-80 kV/m and the HPD simulator generated pulses with horizontal field strengths of 35 kV/m. The documentation of this testing program is presented in reference 10.

(U) Exhibit 4-3 presents the interpolated results used in this analysis. The exhibit indicates that the switch did not have a single physical failure at any of the EMP exposures. However, careful interpretation is required in using these results. The switch tested had several hardware modifications that made it more robust to EMP than a standard 5ESS switch. The administrative module was prone to failure at EMP stress levels as low as 5 kV/m. By adjusting a resistor this problem was overcome, and did not recur through the rest of the test. The original power converter became inoperable when exposed to stress levels above 50 kV/m. With the hardened converter the switch physically survived pulses up to 80 kV/m. Because AT&T plans to make these hardened additions permanent in all future switches, the test data with the hardened updates are used in this analysis. There are no plans to make make these upgrades in the switches which are presently in the network.

EXHIBIT 4-3
(U) Interpolated 5ESS Switch Test Results

STRESS LEVEL (kV/m)	SAMPLE SIZE	FAILURES
10-30	222	0
30-50	199	0
50-70	33	0

(U) Another phenomenon which is not illustrated in Exhibit 4-3 is the performance degradation of the switch. Immediately following an EMP exposure the switch was completely inoperable and then built up capabilities over time. After roughly 30 minutes the switch reached a stable performance level. This regained performance level was generally reduced from the original switch capabilities. Manual intervention was required to reach the normal operating capabilities. The interpolated results of Exhibit 4-3 do not take into account the EMP effects of these reduced capabilities.

(U) All three digital switches are assigned the survivability data of the 5ESS switch. This is a liberal assumption because numerous technical and operational differences exist among the three switches. However, this assumption is necessary in lieu of comprehensive data. This shortcoming is partially addressed with a sensitivity study on the most dominant of the digital switches, the 4ESS.

4.2 (U) TRANSMISSION FACILITIES

(U) EMP test data is available on four types of transmission facilities. A summary of the transmission facility types that are in the network is presented in Exhibit 4-4. The EMP test data does not address all of the types in the exhibit. As with the switches, untested transmission facility types are assigned the survivability of the equipment they most technologically resemble.

EXHIBIT 4-4
(U) Transmission Facility Types

EQUIPMENT TYPE	ASSIGNED EQUIPMENT SURVIVABILITY
L Carrier	L Carrier
N Carrier	L Carrier
T Carrier	T1 Carrier
T4M Carrier	T1 Carrier
Analog Microwave	TD-2 Microwave
Digital Microwave	TD-2 Microwave
Satellite	TD-2 Microwave
Fiber Optics	FT3C Fiber Optics

4.2.1 (U) L4 Coaxial Cable System

(U) The analog L carrier transmission family is designed for high density, long haul applications over great distances. It uses single-sideband amplitude modulation over coaxial cable. EMP testing on the L4 system was conducted by SAFEGUARD Communications Agency in 1973. The tests were conducted at the West Range Laboratory, Fort Huachuca, Arizona and are documented in reference 11. The interpolated results are presented in Exhibit 4-5.

EXHIBIT 4-5
(U) Interpolated L4 Cable Test Results

STRESS LEVEL (kV/m)	SAMPLE SIZE	FAILURES
10-30	151	1
30-50	151	1
50-70	45	24

(U) The test data were not analyzed to compare the detailed test conditions for each measurement with each stress level. Throughout the test, both the equipment configuration and the method of applying the stress was varied. In addition, the EMP simulators did not apply appropriate EMP stress to cables entering the facility, which can result in an understress of the equipment for a given field level. For these reasons it was not possible to separate the data between the low and medium field levels. The low and medium test data results were therefore pooled together as indicated in Exhibit 4-5.

(U) At the higher stress levels the L4 system was susceptible to shutdowns at the power system due to overcurrent and undercurrent effects. Such an occurrence can be deemed a failure because manual intervention was required to restore system operability even though there was no physical damage. Such manual intervention might be impossible during NSEP conditions.

(U) In summary, the L4 system appears robust to EMP effects below 50kV/m and susceptible to them above that level. This statement is solely based on the results of the SAFEGUARD Communications Agency testing program.

4.2.2 (U) <u>T1 Carrier System</u>

(U) In 1962 the first digital transmission line, the T1 carrier, was introduced into the PSN for short haul urban applications. The T1 carrier uses a bipolar signal operating at 1.544 Mbps over cable.

(U) The Defense Nuclear Agency (DNA) sponsored an EMP test program on the T1 carrier system. Reference 12 documents the results of this test. The test data reflect tests performed for both hardened and unhardened elements of the T1 carrier system. The specific elements tested were the line and office repeaters as well as the D4 channel bank. Both field tests and current injection tests were conducted as part of the program. For the purposes of this analysis, the D4 data was extrapolated out of the test data. This is because the D4 equipment is addressed separately, see section 4.3.

(U) The interpolated results of the T1 carrier are presented in Exhibit 4-6. The first set of data presents survivability at the central office location. The second data set portrays the survivability at a repeater location. The two sets are needed because of the structural differences between the central office and repeater equipment facilities. Exhibit 4-6 indicates that the T1 carrier facilities are robust to EMP effects.

EXHIBIT 4-6
(U) Interpolated T1 Carrier Test Results

Central Office Results

STRESS LEVEL (kV/m)	SAMPLE SIZE	FAILURES
10-30	8	0
30-50	6	0
50-70	4	0

Line Repeater Results

STRESS LEVEL (kV/m)	SAMPLE SIZE	FAILURES
10-30	31	0
30-50	20	0
50-70	8	0

(U) Through the testing program the equipment configuration was varied considerably from exposure to exposure. In some cases particular components of the system were taken out. In the interpolated results, consideration was not given into the variances of the test conditions. Still the test program results show that the T1 carrier system is inherently well-designed to withstand EMP effects as it survived all of the EMP exposures.

4.2.3 (U) FT3C Fiber Optic System

(U) The FT3C fiber optic system is a digital transmission facility capable of supporting communications at 90 Mbps through multimode light pulses. The system contains three elements: the optical waveguide cable, the line repeater station, and the central office equipment which terminates the signal. OMNCS supported testing of the FT3C commenced in 1984. Two types of tests were conducted. Field tests were performed at Harry Diamond Labs, Woodbridge, VA, and current injection tests were performed at Bell Labs, Indian Hill, Illinois. The results of these tests are documented in reference 13.

(U) The tests indicate that the power converters at the line repeating stations and central office terminating equipment are very susceptible to EMP effects. Successful operation of these power converters is required in order for the FT3C system to support communications. Hence, a power converter failure implies a FT3C system failure.

(U) The interpolated results, which indicate poor survivability, of the tests are presented in Exhibit 4-7. The small sample sizes reflect that a major portion of the tests were conducted on a FT3C system with hardened power converters, which proved to be robust to EMP. The hardened results are not used in this analysis because there are no plans to incorporate the hardened power converters into either present or future systems. The primary value derived from these tests is that it has been proven that the FT3C fiber optic system can be hardened to EMP effects with the incorporation of a few minor upgrades.

(U) In this analysis all fiber optic transmission facilities, both singlemode and multimode are assigned the survivability data based on the FT3C testing results. The use of fiber optic transmission facilities within the network is expected to increase rapidly, particularly fiber systems using singlemode technology.

EXHIBIT 4-7
(U) Interpolated FT3C Fiber Optic System Test Results

Central Office

STRESS LEVEL (kV/m)	SAMPLE SIZE	FAILURES
10-30	9	4
30-50	3	3
50-70	3	3

Line Repeater Station

STRESS LEVEL (kV/m)	SAMPLE SIZE	FAILURES
10-30	2	2
30-50	2	2
50-70	2	2

4.2.4 (U) TD-2 Microwave System

(U) The TD-2 microwave is a Frequency Division Multiplexed - Frequency Modulated (FDM-FM) analog system. It uses vacuum tube technology and multiplexes 1,500 circuits per radio channel on horizontally polarized beams. The TD-2 system operates in the 3.7-4.2 GHz frequency range. A solid state version, the TD-3, is replacing the TD-2 on an evolutionary basis. EMP testing was conducted on the TD-2 microwave transmission system at Fargo, North Dakota in 1968. The results of this testing program are documented in reference 9.

4.3 (U) ANCILLARY EQUIPMENT - D4 CHANNEL BANK

(U) The function of a D4 channel bank is to perform analog to digital and digital to analog signal conversions. On an analog switch the D4 is interfaced with digital transmission facilities and on a digital switch it interfaces with analog transmission facilities. A growing number of digital switches have internal equipment to perform the A/D conversions, such as the 4ESS which uses the L/T connector for this purpose. Such internal equipment obviates the need for a D4 channel bank. In this analysis a D4 channel bank will only be applied at the interface of digital switches and analog transmission facilities during the simulations. As the network evolves to more digital equipment, the importance of the D4 channel bank is expected to decrease.

(U) EMP testing was conducted on the D4 channel bank in 1986 at the Air Force Weapon Laboratory, Alburquerque, New Mexico. The tests were conducted at the ALECS facility which is capable of producing vertical EMP field strengths between 5-100 kV/m. Documentation on the testing is available in reference 14. The interpolated results are illustrated in Exhibit 4-9. When exposed to a EMP stress of roughly 10 kV/m, the equipment failed. This is the only applicable data point from the tests, hence it is used for all three EMP stress level pockets.

EXHIBIT 4-9
Interpolated D4 Channel Bank Test Results

STRESS LEVEL (kV/m)	SAMPLE SIZE	FAILURES
10-30	1	1
30-50	1	1
50-70	1	1

(U) The rest of the testing focused on hardening the D4 channel bank. By installing Terminal Protection Devices (TPDs) at the interface of exposed cables, the D4 was shown to be robust to EMP effects. Because there are no plans to install TPDs in the network, the hardened D4 channel bank test results are not used in this analysis.

(U) 5.0 EQUIPMENT EMP SENSITIVITY RESULTS

(U) This section presents results of the sensitivity analysis on the 4ESS switch, D4 channel bank, and microwave transmission facilities. These three equipment types are selected by the OMNCS due to their perceived importance in network performance. The individual detailed reasons why each equipment is selected are the following:

- 4ESS Switch- This switch is the backbone of the toll network. Excluding the 133 end offices addressed in this analysis, 4ESS switches comprise roughly 50 percent of the network switches. In addition, the 4ESS switch has not been EMP tested.

- D4 Channel Bank- The D4 channel bank is an analog/ digital interface. In this analysis it is placed between analog switches and digital transmission facilities. It is not placed between digital switches and analog transmission facilities as newer digital switches have their own internal A/D converters. The D4 is still believed to be an important element, especially at the local level, in the network though its importance is on the decline as the network becomes more digital.

- Microwave Transmission Facilities- Sixty-five percent of the network transmission facilities are microwave. However data is only available on the TD-2 microwave facility which is an older analog system based on vacuum tube technology. Of all the microwave systems, many such as the analog TD-3 and digital DR6-30 employ solid state devices which may make them less robust to EMP than the TD-2. Microwave systems are therefore selected in this sensitivity study because of their high prevalence in the network and because data is only available on one of many types of microwave transmission facilities.

5.1 (U) REVIEW OF SIMULATION PROCEDURES

(U) A sensitivity study is conducted separately for the three equipment types. Each equipment is simulated at four discrete survivability rates of 90, 70, 50, and 20 percent. At each survivability rate 50 Monte Carlo replications are conducted at each of the three EMP stress levels. These three stress levels are low 10-30 kV/m, medium 30-50 kV/m, and high 50-70 kV/m.

(U) In addition the connectivity results are calculated from a physical, PSN baseline, and NETS connectivity perspective. The PSN baseline and NETS calculations are with respect to logical connectivity. From the perspective of a telephone user who is concerned with maintaining voice communications, it is logical connectivity that dictates the users calling capabilities. In normal conditions the user will have 100 percent logical connectivity via the normal PSN baseline. However, in an NSEP condition this capability may be drastically reduced. A routing enhancement service such as NETS is designed to increase the users logical connectivity by providing additional routing capabilities.

(U) The network analyzed is composed of 344 switches and the transmission facilities which interconnect them. Of these 344 switches, each switch performs one of four roles: toll, access tandem, point-of-present (POP) or end-office switch. The general function of these switches are as follows:

- End office- The switches to which end-users are connected.

- Access Tandem- The switches to which end-office switches are connected. Access Tandems route users traffic to the particular common carrier that the user is serviced by. In this analysis the common carrier is AT&T.

- POPs- These switches represent the gateway to the toll network. POPs are connected to other POPs and toll switches to route traffic through the toll network.

- Toll Switches- Intermediate switches within the toll network that perform toll network routing. Toll switches are used by POPs to reach the destination POP.

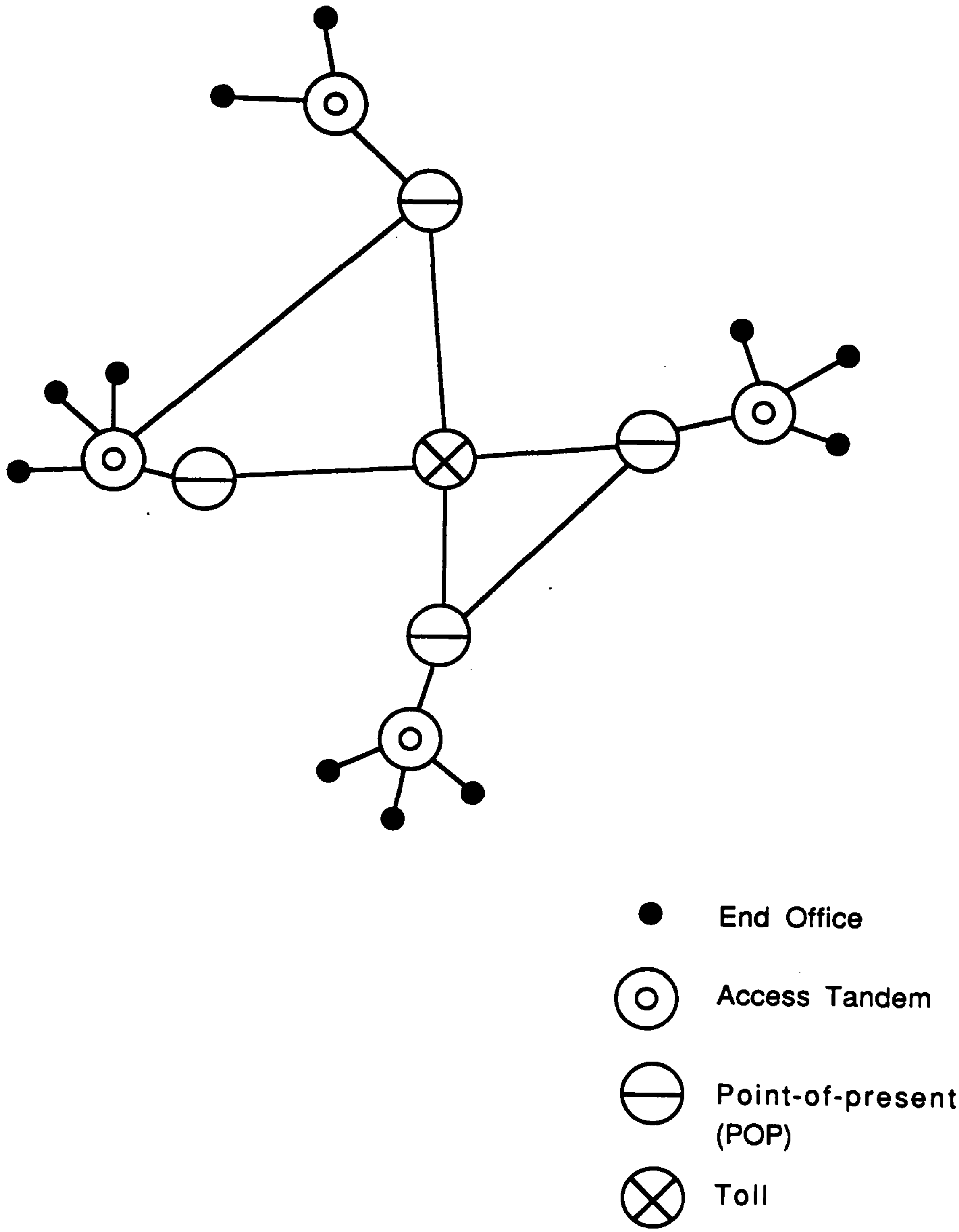
The topology of this switch configuration is presented in Exhibit 5-1. End-users have their telephone lines hooked to the end-office. The end offices are connected to access tandems, which route the end-user to the proper carriers POP, in this case AT&T's POP. Once at the POP, which is the beginning of the toll network, the call is transferred to the destination POP either directly, or indirectly through toll switches. The call is then routed to the destination end-user via the reverse process.

(U) In this analysis the point-pair connectivity metric is calculated for the 124 POPs in the network. This metric is a measure of network performance and is described in section 2.0. However, the other 220 switches still directly affect the POP connectivity because of all the interconnections between the different classes of switches.

(U) Calculating the point-pair connectivity metric based on the POPs is the appropriate approach for this analysis because the POPs are critical to toll network performance. Each end-user is only connected to a single POP, and relies on that POP to support all of its toll level communications.

EXHIBIT 5-1

(U) Network Structure



(U) In summary, this analysis is conducted under the following set of conditions:

- A sensitivity study is conducted on the effects of the 4ESS switch, D4 channel bank and microwave transmission facility survivability on network performance.

- The sensitivity of each equipment is calculated at three EMP stress levels -- low 10-30 kV/m, medium 30-50 kV/m, and high 50-70 kV/m.

- At each stress level a Monte Carlo process of 50 simulations is conducted. The result of the 50 simulations is the mean and standard deviation of network connectivity.

- Network connectivity is defined in terms of point-pair connectivity.

- The network analyzed is comprised of 344 switches and the transmission facilities which interconnect them. The point-pair connectivity metric is calculated for the 124 POPs of the network.

(U) Before interpreting the results that are presented it is important to understand the assumptions which were necessary to conduct this analysis. The network analyzed is comprised of many different types of switches and transmission facilities. However, the OMNCS only has EMP test data on seven of these equipment types. Equipment types for which no EMP test data are available are assigned the survivability characteristics of the equipment they most technically resemble that has been tested. Therefore, each network equipment type is assigned the survivability of one of the seven equipment types that have been tested. This assignment process produces an unquantified source of error in the results.

(U) Another source of error is the test data itself. The equipment EMP tests were conducted by a variety of government agencies, for different purposes, and under different test conditions. The network level approach requires that this data be viewed with a consistent format. An interpolation procedure was therefore required to interpret this array of data into the consistent format. This interpolation procedure inherently induces additional error, which is documented in section 4.0.

5.2 (U) NETWORK CONNECTIVITY

(U) The NCAM model was initially run with each equipment type surviving EMP as described in section 4.0, i.e. no sensitivity studies were conducted on any of the equipment types. The results of these simulations are presented in Exhibit 5-2. Each group of three bar graphs represents the point-pair connectivity of the network to a range "bin" of EMP stress levels following simulated EMP exposure. The low group portrays EMP connectivity in the range of 10-30 kV/m. Likewise the medium group portrays connectivity in the range of 30-50 kV/m; and the high group portrays connectivity in the range of 50-70 kV/m. Within each group a total of 50 Monte Carlo replications were conducted, where each network equipment was assumed to be exposed to a uniform EMP stress level. Finally, it is noteworthy that most EMP effects analysts believe that exposure to stress levels above 50 kV/m is very unlikely, which make the high-level exposure level a worst case scenario.

(U) Within each group, the solid bar represents physical, the striped bar represents PSN baseline, and the dotted bar represents NETS mean point-pair connectivity following the 50 Monte Carlo simulations. Note that in the low and medium stress level bins the degradation effects appear to be minimal. The reason for this is that the EMP test data (section 4.0) dictate that very few equipment fail at these two levels. Since few equipment fail, both the physical and PSN baseline connectivities

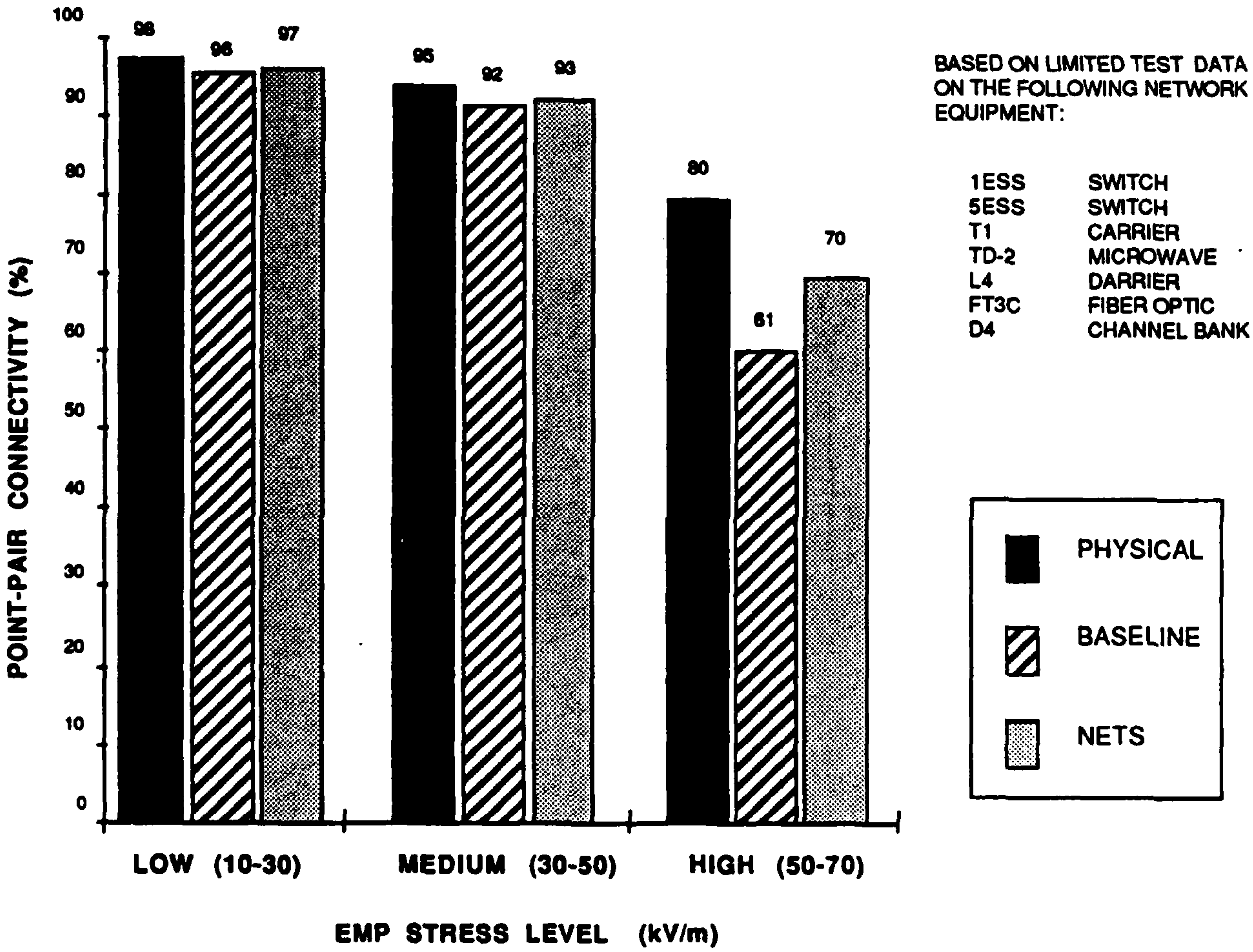
Exhibit 5-2

(U) Network Connectivity:

No Equipment Sensitivity Study

POINT-PAIR NETWORK CONNECTIVITY:

NO EQUIPMENT SENSITIVITY STUDY



remain high. In such situations, from solely an EMP perspective, there does not appear to be a need for NETS. The advantages of the NETS routing enhancement become apparent as a greater proportion of equipment fail, which occurs at the high stress level. As NETS makes greater use of surviving physical resources at this level, the logical connectivity improves from 61 to 70 percent, a 14.7 percent improvement.

(U) It is restated that many equipment types in the network have not been EMP tested, and are assigned the survivability of the equipment they most technologically resemble which has been EMP tested. In addition the test data itself is a source of error due to testing procedure shortcomings and the interpolation of the test data conducted in this analyses. All of these uncertainties and assumptions must be acknowledged when interpreting the results of Exhibit 5-2, as well the results presented in the rest of this section.

(U) A table format of the non-sensitivity network level results is presented in Exhibit 5-3. Along with the mean point-pair connectivity of the nine Monte Carlo procedures, the standard deviation among the 50 iterations is also provided. The standard deviation specifies the expected spread of the 50 individual point-pair calculations around the mean.

EXHIBIT 5-3

(U) Table Format of No Sensitivity Study

POINT-PAIR CONNECTIVITY AND STANDARD DEVIATION

PHYSICAL			BASELINE			NETS		
LOW	MED	HIGH	LOW	MED	HIGH	LOW	MED	HIGH
98/2.1	95/2.2	80/3.9	96/2.3	92/2.5	61/6.2	97/2.3	93/2. 3	70.3/5.7

5.3 4ESS SWITCH SENSITIVITY STUDY

(U) A 4ESS switch study was conducted because it is a prevalent switch in the network and it has not been EMP tested. In this sensitivity study it was assumed to survive over a range of values; specifically, 90, 70, 50 and 20 percent. It is the purpose of this sensitivity study to show how dependent network performance is on the performance of the 4ESS switch.

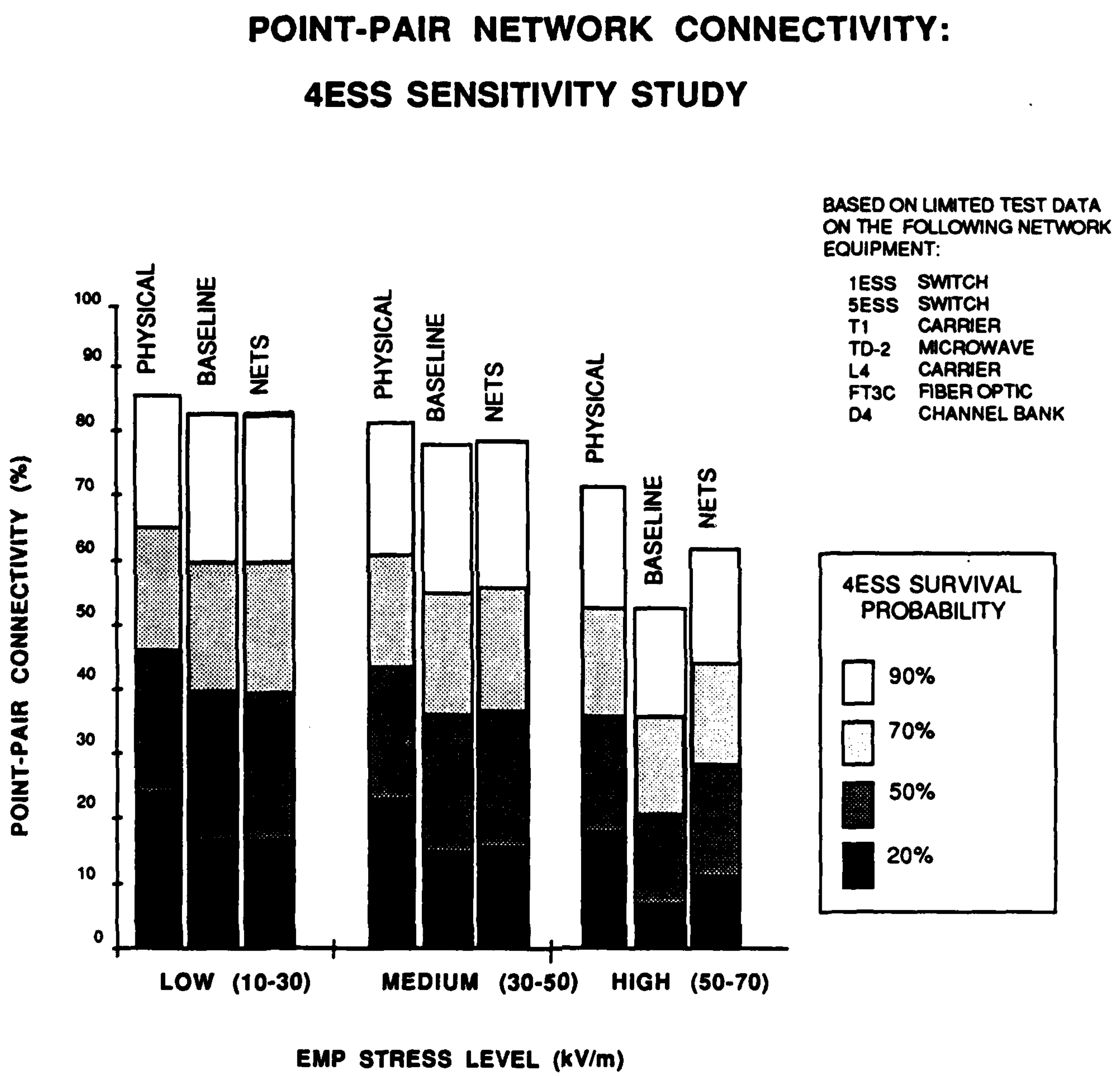
(U) As before, the network is simulated at the three EMP stress levels, and at each stress level the physical, baseline, and NETS connectivity are calculated. Therefore a total of 12 Monte Carlo processes are conducted for the 4ESS sensitivity study, as four survivability rates are assumed for each of the three stress levels. Recall that each Monte Carlo process consists of 50 discrete simulations.

(U) 4ESS switch sensitivity simulation results are presented in Exhibit 5-4. This is similar to Exhibit 5-2, except that at each bar there are four, rather than one, connectivity results. Each of the four results correspond to the point-pair connectivity at a discrete 4ESS survival rate. The darkest region represents the lowest survivability rate (20 percent), while subsequent lighter regions of the bar graphs represent higher survivability rates of 50, 70 and 90 percent. Finally, the 4ESS survivability rates vary uniformly (from 20-90 percent) over the three EMP stress levels. For example, at the lightest region, the 4ESS switch survives at a 90 percent rate at all three stress levels. The reason that the connectivity metrics decrease with increasing EMP field strengths at the same 4ESS survivability rate is because the other network equipment fail at higher rates.

(U) At each of the three stress levels, the results of Exhibit 5-4 indicate that there is approximately a linear

EXHIBIT 5-4

(U) Network Connectivity:
4ESS Switch Sensitivity Study



relationship between point-pair connectivity and 4ESS survival rate. This is apparent by the rather equal spacings of point-pair connectivity over the different survivability rates. For example, at the low stress level the PSN baseline connectivity varies from 83, to 60, to 40, to 17 percent, at 4ESS survivability rates of 90, 70, 50 and 20 percent, respectively. This appears to follow a linear relationship as the connectivity roughly decreases 20 percent for each decreasing survivability rate.

(U) At the low and medium stress levels NETS does not appear to provide any significant additional logical connectivity compared to the standard PSN baseline. This is because the only equipment that is not surviving at a very high rate (from section 3.0 on the EMP test data) is the 4ESS switch. In addition, the 4ESS switches provide many of the NETS services. This combination of events does not let the NETS additional routing capabilities come into effect because only the NETS equipment are failing at a significant rate.

(U) At the high stress levels, non-4ESS equipment is failing at aprreciable rates, and NETS has the opportunity to improve connectivity with the surviving resources. Referring to the 70 percent survivability rate, NETS improves logical connectivity from 36 to 44 percent, an increase of 22.2 percent.

(U) The results of this 4ESS sensitivity study illustrate that the performance of the 4ESS switch is extremely critical to the performance of the network. This is primarily due to the following three reasons:

- Fifty percent of the toll network switches are 4ESS switches

- Many of the NETS resources are located in 4ESS switches

- In general, 4ESS switches are highly interconnected, i.e. they contain many trunk lines.

A table format of the sensitivity study results, complete with the standard deviation of the Monte Carlo procedure, is presented in Exhibit 5-5.

EXHIBIT 5-5
(U) Table Format of 4ESS Switch
Sensitivity Study Results

POINT-PAIR CONNECTIVITY AND STANDARD DEVIATION

NETWORK ELEMENT SURVIVABILITY	PHYSICAL			BASELINE			NETS		
4ESS	LOW	MED	HIGH	LOW	MED	HIGH	LOW	MED	HIGH
.90	86/4.2	82/4.6	72/4.8	83/4.7	78/4.7	53/6.1	83/4.6	79/4.7	62/5.1
.70	65/5.3	61/4.8	53/5.9	60/5.4	55/4.7	36/5.9	60/5.3	56/4.7	44/5.3
.50	47/4.8	44/4.7	36/4.8	40/4.5	37/4.6	21/5.1	40/4.5	37/4.6	28/4.7
.20	24/3.0	23/3.0	18/2.9	17/2.5	16/2.7	7/2.6	17/2.5	16/2.5	11/2.6

5.4 (U) D4 CHANNEL BANK SENSITIVITY STUDY

(U) A D4 channel bank is an interface between analog switches and digital transmission facilities, or analog transmission facilities and digital switches. In this analysis it is only placed between analog switches and digital transmission facilities. The D4 is not placed between digital switches and analog transmission facilities because many digital switches have their own internal equipment to handle the job of the D4, such as the 4ESS which uses the L/T connector. A sensitivity analysis is performed on the D4 because there is only minimal EMP test data available on it.

(U) The results of the D4 channel bank sensitivity study are presented in Exhibit 5-6. There is practically no degradation on network connectivity as the D4 survivability degrades from 90 to 20 percent for all three EMP stress levels. This is because there are so few analog switches, and that the network is still dominated by analog transmission facilities. These results are only applicable at the toll level. The D4 is still belived to be an integral part of the PSN, especially at the local level.

(U) A table summary of the D4 channel bank sensitivity studies, which includes the standard deviations of the Monte Carlo simulations, is presented in Exhibit 5-7.

5.5 MICROWAVE SENSITIVITY STUDY

(U) Sixty-five percent of the transmission facilities in the AT&T toll network are microwave systems. In addition, the only available microwave system EMP test data is on an older vacuum tube based system. The PSN is composed of many versions of microwave systems, based on technologies ranging from analog vacuum tube systems to digital solid state devices. Examples of the numerous existing microwave systems include the short haul analog TM-2 and TN-1, the long-haul analog TD-2 and TH-3, and the digital DR11-40 systems. Given the limited test data, it is appropriate to conduct a sensitivity study on microwave transmission facilities.

EXHIBIT 5-6

(U) Network Connectivity:

D4 Channel Bank Sensitivity Study

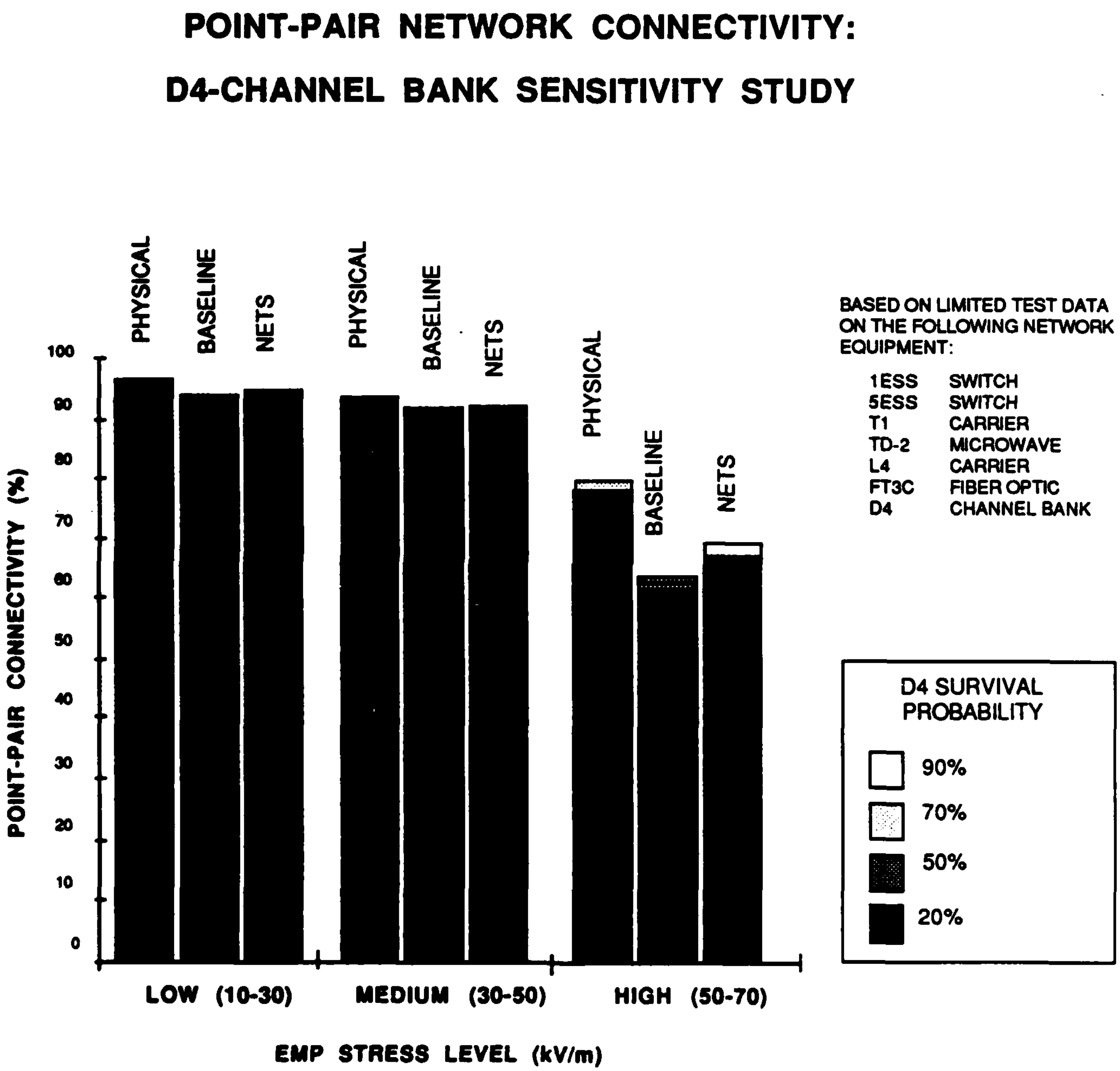


EXHIBIT 5-7

(U) Table Format of D4 Channel Bank
Sensitivity Study Results

POINT-PAIR CONNECTIVITY AND STANDARD DEVIATION

NETWORK ELEMENT SURVIVABILITY	PHYSICAL			BASELINE			NETS		
D4	LOW	MED	HIGH	LOW	MED	HIGH	LOW	MED	HIGH
.90	97/1.5	94/2.3	80/4.5	95/2.2	92/2.5	64/5.0	96/2.1	92/2.5	72/4.6
.70	97/1.5	94/2.2	80/4.5	95/2.2	92/2.4	63/5.1	96/2.0	92/2.5	72/4.6
.50	97/1.5	94/2.2	79/4.6	95/2.2	92/2.4	63/5.2	96/2.0	92/2.6	71/4.6
.20	97/1.5	94/2.2	79/4.8	95/2.2	92/2.4	62/5.1	96/2.0	92/2.6	71/4.7

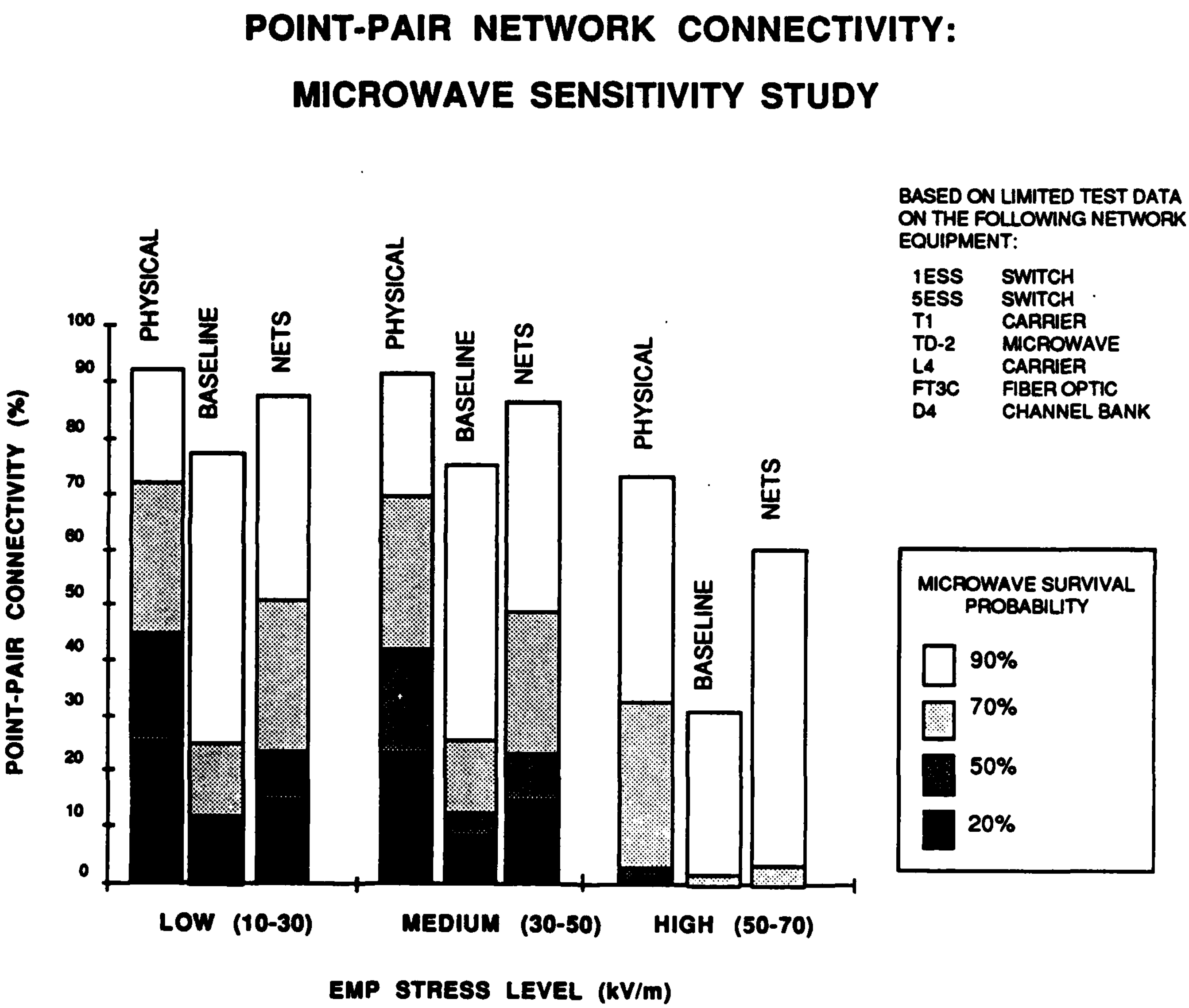
(U) Exhibit 5-8 presents the results of the microwave transmission facility sensitivity study. The results indicate that network performance is extremely critical to the performance of network microwave systems. In addition, the NETS connectivity is always significantly higher than the PSN baseline connectivity. For example, at a 70 percent survivability rate at the low EMP stress level, NETS improves logical connectivity from 26 to 51 percent, corresponding to an improvement of 96.1 percent. NETS improves connectivity at such a high rate because most of the switches, where NETS capabilities are stored, survive; and NETS makes greater use of the surviving transmission facilities.

(U) Another interesting result of the microwave simulations occurs at the high stress level. When 50 percent or less of the microwave facilities survive, the connectivity of both the PSN

EXHIBIT 5-8

(U) Network Connectivity:

Microwave Transmission Facility Sensitivity Study



baseline and NETS is so poor (low) that they can not even be represented in Exhibit 5-8. They must be read from the table format diagram, shown in Exhibit 5-9. This exhibit presents the exact point-pair mean and standard deviation of all the simulation runs. Note that at a 50 percent survivability rate, the PSN baseline and NETS point-pair connectivity are only .3 and .4 percent, respectively.

EXHIBIT 5-9

(U) Table Format of Microwave Transmission Facility Study Results

POINT-PAIR CONNECTIVITY AND STANDARD DEVIATION

NETWORK ELEMENT SURVIVABILITY	PHYSICAL			BASELINE			NETS		
MICROWAVE	LOW	MED	HIGH	LOW	MED	HIGH	LOW	MED	HIGH
.90	93/2.5	91/3.3	75/5.8	78/5.8	75/6.0	32/5.5	88/3.4	86/3.8	61/6.9
.70	72/4.7	69/6.2	33/10.5	26/4.5	26/4.2	2.1/0.8	51/7.4	49/7.4	4/2.8
.50	45/5.0	42/4.3	3.5/1.7	13/1.8	13/1.7	0.3/0.2	24/3.6	23/3.9	0.4/0.2
.20	26/2.4	23/2.4	.65/.23	10/0.9	9/0.9	.15/0.1	15/1.5	15/1.7	.15/0.1

(U) 6.0 CONCLUSIONS AND RECOMMENDATIONS

(U) This analysis has conducted a sensitivity study which measures how critical the EMP survivabilities of the 4ESS switch, the D4 channel bank, and the microwave transmission facilities are to network performance. Network performance was measured by calculating the point-pair connectivity metric of multiple computer simulation runs. The network analyzed in this analysis was the toll portion of the AT&T network.

(U) For the 4ESS switch, results of this analysis indicated that this switch is very critical to network performance for the following reasons:

- The switch is highly prevalent in the network.
- The switch is generally highly interconnected with other switches in the network. Therefore if one 4ESS switch fails, there is a significant second order affect which degrades the connectivity of other network switches.
- With respect to NETS, 4ESS survivability is critical because many NETS capabilities are stored in 4ESS switches. If network 4ESS switches fail, the dependent NETS capabilities do not have the chance to operate.

(U) The D4 channel bank does not appear to be a critical network equipment. This is so for the following reasons:

- There are presently not many D4 channel banks in the <u>toll</u> network.
- The importance of the D4 is on the decline. As the network migrates digitally there will be less of a need for A/D and D/A conversions. In addition most of the newer digital switches have their own internal elements

which perform D4 channel bank functions when interfaced with analog transmission facilities.

It is stressed that these conclusions are only applicable for the toll level. It is believed that the D4 channel bank is still a significant element at the local level, and that local level survivability is required if NSEP telecommunication users are to reach the toll level.

(U) The survivability of the PSN's microwave transmission facilities is critical for high PSN performance. The following reasons substantiate this claim:

- Sixty-five percent of the toll level transmission facilities are microwave based.

- Of the logical connections between switches, well over 65 percent of them employ some type of microwave based system. This is because a logical connection often uses multiple transmission facility types between the switch end points, and a failure at any segment of the connection constitutes a logical connection failure.

In addition, the microwave transmission facility sensitivity study also showed the capabilities of NETS. In these simulations very few of the NETS switches were failing, but many of the transmission facilities were failing. NETS switches went on to make greater use of surviving network equipment providing substantial increased logical connectivity compared to the normal PSN baseline.

(U) Results of these sensitivity studies lead to the following recommendations. Implementation of these recommendations will lead to additional confidence in the network level assessments on the effects of EMP on network connectivity. It will also provide greater understanding on the benefits that can be derived from NETS when the PSN is exposed to EMP.

- EMP testing of the 4ESS switching system. This switch is the most prevalent switch in the AT&T toll network and is also the switch type presently envisioned to store many NETS capabilities. It is therefore of great importance to understand how the 4ESS switch responds to EMP exposure, as illustrated in the sensitivity study. Due to the intricacies of the equipment, the best way to understand the EMP effects on the 4ESS is to perform EMP testing on it. In lieu of EMP test data, present OMNCS analyses assume that the 4ESS switch responds to EMP effects as does the 5ESS switch. This assumption has the potential to induce significant errors in the network level connectivity results.

- EMP testing of a solid state microwave transmission facility. Analyses results also indicate that network connectivity is closely correlated with the performance of its microwave transmission facilities. However, EMP test data is only available for an older vacuum tube based system while much of the network is comprised of solid state based microwave transmission facilities. It is therefore suggested that EMP testing of a solid state equipment, which is generally more susceptible to EMP degradation than a vacuum tube system, be conducted.

(U) In addition to these testing recommendations, it is suggested that future network level EMP analyses take into account the partial degradation of network switches. This is particularly important with digital switches, which dominate the toll network, as suggested in a report documenting the 5ESS switch testing results (reference 11). Partial switch degradation is a recently witnessed EMP phenomenon noticed at the 5ESS EMP tests. However, this analysis only addressed equipment physical survivability. Neglecting partial switch degradation, as done in this analysis, generally leads to optimistic network level performance results.

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END

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DTIC