ANALYZING THE ROBUSTNESS OF TELECOMMUNICATION NETWORKS

by

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(ABSTRACT)

This project report defines network robustness and discusses capability indicators that could be used to analyze network robustness. Growing dependence on telecommunication networks and recent network outages have focused attention on network robustness. The National Communications System (NCS), a confederation of 23 Federal departments and agencies, has been concerned with network robustness since its formation in 1963. The NCS is developing and implementing systems and services that enhance the capability of the public switched networks to support critical Government communication requirements during times of crisis or emergency. Quantitative indicators of network robustness are needed to analyze the benefits of these enhancements. This project proposes a set of candidate capability indicators that could be used by the NCS in future analyses of the public switched networks with and without network enhancements.

ACKNOWLEDGEMENTS

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1. INTRODUCTION

The purpose of this systems engineering project is to define capability indicators for analyzing the robustness of telecommunication networks. The results of this project could be used by the National Communications System (NCS), a Federal Government agency charged with ensuring that the Nation's telecommunications infrastructure can support critical communication requirements during times of crisis or emergency. This topic was selected because of a recognized need to change the analysis approach currently employed by the NCS and its Systems Engineering and Technical Assistance Contractor, Booz•Allen & Hamilton. A revised analysis approach, including a redefined set of capability indicators, is needed because of the changing political climate, evolving telecommunications technology, and an expanding set of NCS analysis requirements.

1.1 BACKGROUND

Recent, highly-publicized telecommunications network outages have focused the attention of the telecommunications industry and its customers on the robustness of the Nation's telecommunications infrastructure. A National Research Council report on the vulnerability of the public switched networks (PSN) contains the following statement:

> Today it is universally acknowledged that the United States is becoming more and more an information society, and that telecommunications and information networks are essential components of an information society's supporting infrastructure. Networks of the future will be increasingly relied on for a remarkable variety of voice, data, and video services. It is thus of considerable concern that, because of powerful trends in the evolution of the nation's telecommunications and information networks, they are becoming more vulnerable to serious interruptions of service (National Research Council 1989).

The NCS has been concerned with the vulnerability of the Nation's telecommunication networks since its formation in 1963. The NCS was established by President Kennedy as a result of shortcomings in emergency communications experienced during the Cuban Missile Crisis. The **NCS** is a confederation of 23 Federal departments and agencies with telecommunication requirements and assets critical to the national security and emergency preparedness (NS/EP) posture of the United States. The NCS is charged with providing the necessary communications to support the Government's NS/EP telecommunication needs under all conditions. NS/EP telecommunications support Government operations during times of crisis or emergency, including the recovery phase following a crisis or emergency. The NCS is not responsible for the telecommunication systems and services that support Federal Government communications under normal operating conditions. The organization of the NCS is depicted in Figure 1.

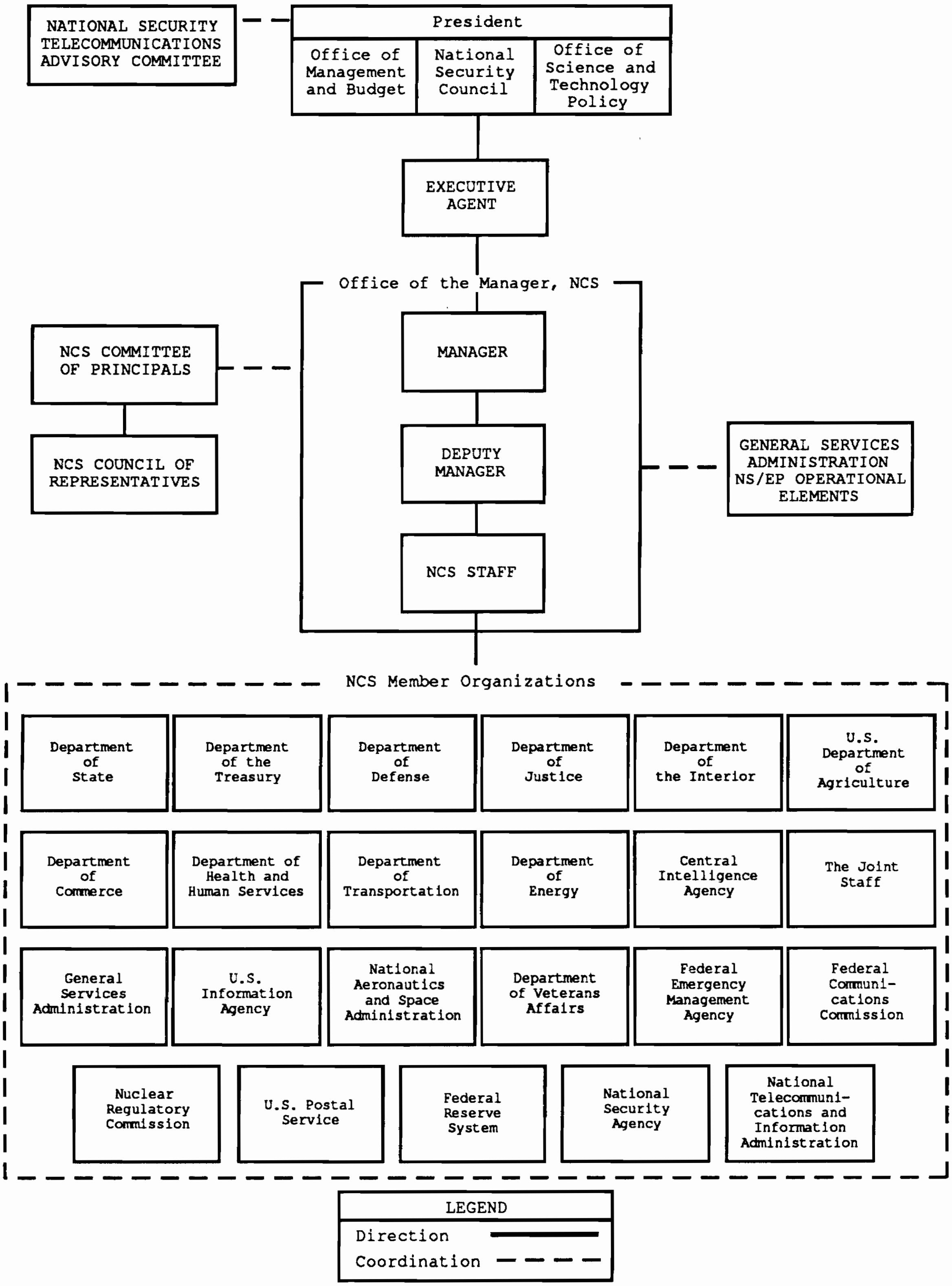


FIGURE 1: National Communications System Organization

The NCS is enhancing the capabilities of the Nation's telecommunication networks to ensure that NS/EP telecommunication requirements are met when these networks operate under stress conditions. In other words, the NCS is trying to improve the robustness of the PSN, where **network robustness** is defined as the capability of a network to maintain an acceptable level of service during stress conditions or to restore an acceptable level of service soon after network stress has occurred. The **PSN** includes local and long distance telephone networks, cellular networks, and public data networks. The NCS is building upon the significant capabilities of the PSN, rather than designing a complete, private network for critical Government users. **Stress conditions** cause physical damage or traffic congestion in the PSN. There is a wide range of threats to the network that can result in stress conditions. Examples of threats to the network are unintentional cable cuts, equipment sabotage, natural disasters, and nuclear war.

Systems engineering refers to the process and activities involved in transforming an operational need into a cost-effective system that meets that need. If the purpose of systems engineering is to develop a cost-effective system to meet an identified need, then there must be an ability to define and measure system effectiveness and to verify that the need is met. **System effectiveness** is defined as "the ability of a system to do the job for which it was intended" (Blanchard and Fabrycky 1981).

The NCS must define and use system effectiveness indicators to determine if it is accomplishing its mission in a cost-effective manner. The mission of the NCS is to enhance existing telecommunication systems to meet the need for continued communications supporting critical Government functions under stress conditions. Therefore, the NCS needs capability indicators to gauge the robustness of the PSN without enhancements and to analyze the benefits, in terms of improved network robustness, of Government-funded enhancements.

The term **capability indicator** is used in this report because the NCS is enhancing the inherent capability of the PSN. The NCS is not monitoring network performance under normal operating conditions. Therefore, the capability indicators defined in this project report may or may not apply to networks operating in a normal environment (i.e., no stress on the network). The robustness capability of the PSN with and without enhancements is a function of certain network characteristics and network stress conditions.

The NCS could use the capability indicators defined in this project to evaluate alternative enhancements in order to select the most cost-effective one(s). These indicators should be quantifiable in objective terms and can be combined with subjective evaluation criteria in the trade-off analysis process. The NCS could also use the capability indicators when it performs a supporting analysis for its largest program, the National Level NS/EP Telecommunications Program (NLP). The **NLP** comprises multiple component programs aimed at increasing the robustness of the PSN for NS/EP telecommunications. For this supporting analysis, the NCS examines program costs and uses modeling tools to determine increases in network robustness provided by the NLP. The results of the NLP supporting analysis are reviewed by representatives from the 23 NCS member organizations.

The NCS is charged with ensuring that a capability exists to support NS/EP telecommunications, but the NCS may not be able to fully exercise this capability in the absence of actual stress conditions. Therefore, the NCS cannot collect actual performance data under controlled conditions. The NCS must predict values for capability indicators from models of the PSN with and without enhancements for various stress scenarios.

1.2 PROJECT OBJECTIVES

The purpose of this project is to define capability indicators relating to network robustness that could be used in NCS analyses. The following are specific project objectives:

- Develop a qualitative understanding of network robustness
- Identify capability indicators for network robustness and evaluate their applicability to the NCS's analysis requirements
- Recommend a set of indicators for use by the NCS in cost/effectiveness analyses of its programs and initiatives.

The NCS should be able to use the capability indicators to analyze the robustness of the PSN under a range of stress conditions. The indicators should differentiate among alternative enhancements and be feasible to evaluate in the modeling process. In addition, these indicators should be easy to understand by NCS decision-makers.

1.3 SCOPE

This project examines capability indicators for network robustness. Because these indicators are tailored to the specific analysis requirements of the NCS, they may not be applicable to all types of telecommunication networks. In addition, the indicators may or may not be applicable to networks in a normal operating environment (i.e., when the networks are not stressed).

Capability indicators are defined for public circuit-switched and packet-switched networks. Current NCS planning and analysis efforts center on public circuit-switched telephone networks, including cellular networks. However, due to expected growth in data communication requirements, public packet-switched data networks are also included in the discussion of the PSN.

The project focuses on robustness, a key aspect of system effectiveness for NS/EP applications. Robustness is not the only consideration in evaluating telecommunication network enhancements. Other evaluation criteria, such as cost, speed, and security, are not addressed in this report.

The purpose of this project is to define quantifiable indicators for analyzing network capability under stress conditions. The relative importance of these indicators and minimum acceptable values both depend heavily on the specific analysis application—the kind of network, types of threats, and the time horizon being considered. Therefore, defining the importance of indicators and establishing minimum acceptable values are beyond the scope of this project. Logical next steps to this project are to discuss the robustness indicators with NCS decision-makers and to adapt network modeling tools to accommodate selected indicators.

2. REVIEW OF LITERATURE

This section provides an overview of the literature reviewed during the course of this project. The literature can be grouped into three general categories:

- Literature on the NCS mission, NS/EP telecommunication requirements, and previous NCS analyses
- Literature on systems engineering and decision analysis
- Literature on the PSN, performance measures and capability indicators for telecommunication networks, and techniques for designing robust networks.

Literature on the NCS mission and the NS/EP telecommunication requirements includes high-level policy guidance and technical studies conducted by the NCS and its support contractors. Policy guidance from the Executive Office of the President charges the NCS with ensuring that NS/EP telecommunication requirements can be met under all circumstances. This guidance specifies the desired characteristics of the Nation's telecommunications infrastructure, such as connectivity and survivability. However, it does not explain these terms or establish minimum levels of capability for these characteristics.

Previous NCS analyses have focused on the NLP. However, there is a need to analyze enhancements to the PSN that are not part of the NLP. An expanded set of enhancements may require an expanded set of capability indicators. Very few indicators were used in past NLP analyses, and only one type of stress condition was considered—nuclear attack. The documentation on these analyses does not address the rationale for the use of specific indicators, nor does it trace the indicators back to the NCS mission and the NS/EP requirements.

Literature on the systems engineering process was reviewed to understand the role of system effectiveness indicators in system design, development, and operation. This literature includes definitions of common system effectiveness indicators (e.g., reliability, availability). The information proved helpful in developing a methodology for defining and evaluating network robustness indicators. However, the activities of the NCS are not entirely consistent with the classical systems engineering process. The NCS is not developing a "black box" to meet an operational need. The NCS is trying to enhance the PSN, which is an extremely large and complex system. The PSN developed and continues to evolve to meet the day-to-day needs of millions of customers and to generate profits for the telecommunication carriers. The NCS wants to use the PSN to meet the needs of a few thousand critical users. Due to the nature of NS/EP telecommunications, the use of the PSN to meet these needs may never be completely tested. In addition, many of the techniques for enhancing the robustness of the PSN conflict with the economic interests of the carriers. The levels of robustness desired by the NCS are much greater than levels considered cost effective by carriers for their networks. Therefore, these enhancements must be subsidized by the Government.

Literature on decision analysis was reviewed to understand the process of multi-attribute analysis. An objective of this project is to recommend a set of capability indicators and to provide guidance on their use in analyses of the PSN with and without enhancements. The NCS's problem differs from the examples in the literature in two ways:

- The NCS is not choosing one alternative from a set of mutually exclusive alternatives. Instead, the NCS is trying to select a cost-effective set of enhancements.

- The NCS is considering numerous enhancements that cannot be evaluated consistently. Different types of enhancements require different sets of capability indicators. In addition, the NCS must consider a broad range of stress conditions. An enhancement that is effective for one type of emergency may not be effective for other emergencies.

The third category of literature reviewed pertains to the technology of the PSN, network design considerations, network performance measures, and network capability indicators. A review of literature revealed that there is significant concern about the vulnerability of the networks. The Federal Communications Commission recently formed an advisory committee on network reliability, and the American National Standards Institute (ANSI) drafted a report on network survivability performance.

Although changes in technology can make the PSN more vulnerable, for instance by increasing the concentration of traffic on fiber optic transmission links, technology is also creating opportunities for increasing network robustness. Several articles proposed techniques for improved robustness, such as the use of digital cross-connects to reroute traffic around a node or link failure or designing networks with self-healing rings. These articles focus on network design and system capability indicators used in design. The articles often assume that a network needs only to be protected against single failures. The NCS is not designing a private network, but rather it is trying to assess the robustness of the existing PSN and to enhance the capabilities of the PSN in support of NS/EP telecommunications. In addition, the NCS is concerned with the capability of the PSN to maintain or restore NS/EP telecommunications service under extreme stress conditions (i.e., numerous failures).

Technical literature reviewed also described network performance measures used by the carriers to monitor actual system performance. The NCS is not monitoring actual performance. The NCS needs capability indicators to predict the level of robustness of the networks.

The review of technical literature revealed inconsistencies in the use of terms such as reliability, survivability, and robustness. The terms "robust" and "robustness" are used frequently in the literature without further definition or explanation. This project defines robustness in a way that is useful to the NCS.

3. MATERIALS AND METHODS

The basic project methodology is depicted in Figure 2. The steps outlined in the figure are described in the following paragraphs.

STEP 1: Review NCS Mission and NS/EP Telecommunications Requirements. The objectives of this step are to better understand the mission of the NCS, the service requirements of NS/EP telecommunication users, and the desired system characteristics of an enhanced PSN. The first activity in this step is to review national policy related to the creation and mission of the NCS. The next activity is to review documentation on the NS/EP telecommunication user requirements. The capability indicators developed in later steps should relate to the NCS mission and NS/EP service requirements.

STEP 2: Characterize Systems to be Analyzed. The purpose of this step is to describe the "systems" that the NCS must analyze. Capability indicators should be relevant to these systems (i.e., the PSN with and without enhancements). For example, the NCS does not have programs to improve transmission line quality. Therefore, the NCS is not particularly concerned with measures for transmission line quality, such as signal-to-noise ratio and attenuation

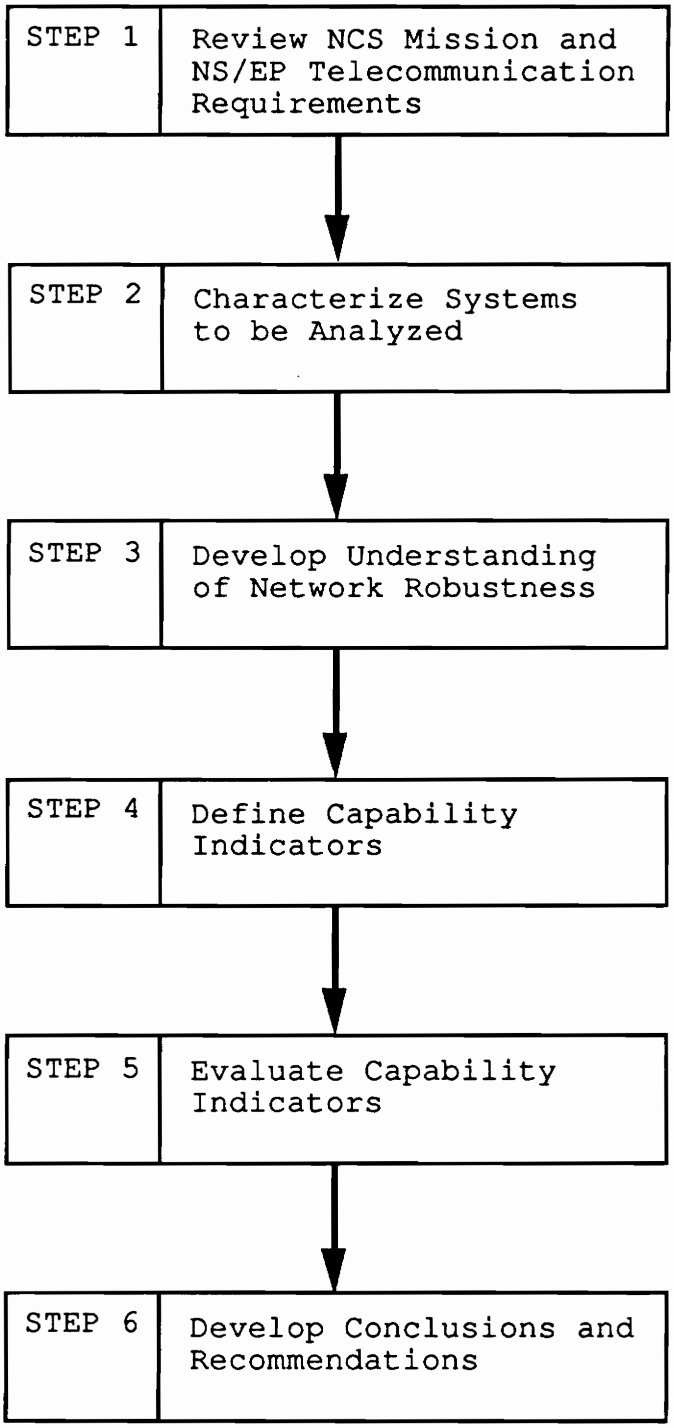


FIGURE 2: Project Methodology

distortion. The outputs of this step will be descriptions of the PSN and the NCS programs and initiatives to enhance the PSN. Robustness refers to the capability of a network under stress conditions. Therefore, another output of this step is a description of stress conditions.

STEP 3: Develop Understanding of Network Robustness. Information gathered in the first two steps is used to develop a qualitative understanding of network robustness. An understanding of network robustness starts with a definition of robustness. The definition is used to derive a list of characteristics related to network robustness. The next step in the process is to define one or more capability indicators for each of the characteristics.

STEP 4: Define Capability Indicators. The purpose of this step is to define potential capability indicators for network robustness. The first activity under this step is to identify indicators that have been used in previous NCS analyses. Next, technical literature is scanned to identify other indicators or performance measures that could apply to network robustness. If necessary, modified or new indicators are proposed. The result of this step is a list of candidate indicators of network robustness.

STEP 5: Evaluate Capability Indicators. The objective of this step is evaluate candidate capability indicators to determine their applicability to the NCS's analysis requirements. The candidate indicators are evaluated based on the following criteria:

- Relevance
- Simplicity
- Modeling complexity
- Sensitivity to specific types of network stress.

Capability indicators should be relevant to the NCS's analysis requirements. In other words, they should relate to NS/EP requirements and NCS concerns. Simplicity is important because the NCS must be able to explain analysis results to a large audience with different levels of technical understanding. Modeling complexity refers to the feasibility of evaluating measures through network modeling and simulation. The changing threat environment emphasizes the need for capability indicators that can be evaluated for a range of stress conditions.

STEP 6: Develop Conclusions and Recommendations. The purpose of this step is to recommend a set of capability indicators based on the findings of Step 5. Another objective of this step is to discuss considerations for selecting indicators for specific analysis applications. Recommended next steps are developed.

4. DISCUSSION

This section discusses the policy guidance and requirements driving NS/EP telecommunication planning and implementation efforts, describes the systems to be analyzed by the NCS, defines network robustness, and proposes candidate capability indicators for analyzing the robustness of the PSN with and without enhancements. An understanding of the systems to be analyzed and a definition of robustness are required before capability indicators can be developed.

4.1 SYSTEM DESCRIPTION

Capability indicators cannot be defined until the purpose of a system is well understood. This section begins with an overview of the NCS mission and NS/EP telecommunication requirements. This overview is followed by a description of the systems to be analyzed—the PSN with and without enhancements. A four-layer network framework is described, as well as network stress conditions. The framework is used in the explanations of network robustness characteristics and indicators.

4.1.1 Mission Analysis and System Requirements

The NCS was established in 1963 in the aftermath of the Cuban Missile Crisis. A Presidential Memorandum, signed on August 21, 1963, created the NCS to ensure "the necessary communications for the Federal Government under all conditions ranging from a normal situation to national emergencies and international crises, including nuclear attack" (White House Memorandum 1963). The NCS mission was further defined by President Carter and President Reagan. This additional guidance states that the national telecommunications infrastructure must possess the necessary combination of connectivity, redundancy, mobility, interoperability, restorability, hardness, and security to support national security leadership and allow Federal agencies to accomplish their wartime and nonwartime functions.

Executive Order 12472, issued in 1984, assigns the NCS the mission of coordinating the planning and provisioning of NS/EP telecommunications for the Federal Government under all circumstances, including crisis or emergency, attack, recovery, and reconstitution (Executive Order 12472 1984). NS/EP telecommunication services support Presidential communications, continuity of government operations, worldwide intelligence collection and diplomacy, the emergency functions of Federal agencies, the Emergency Broadcast System, and State emergency operations centers. Executive Order 12472 also assigns specific responsibilities to the Manager, NCS. The Manager, NCS is charged with the development of an evolutionary telecommunications architecture to meet NS/EP telecommunication needs and the analysis of improved approaches to assist Federal organizations in fulfilling NS/EP telecommunication objectives.

More recent policy guidance defined six functional requirements for NS/EP telecommunications service (White House Memorandum 1991). These requirements, which are listed in Table 1, describe necessary capabilities and characteristics of an NS/EP telecommunications service.

The Office of the Manager, NCS, has worked with the 23 NCS member organizations to define requirements related to type of service, quantity of lines, and locations to be served. NCS member organizations have submitted requirements for more than 20,000 lines at approximately 7,000 locations. NCS member organizations currently have requirements for switched voice and data communications and for dedicated (i.e., point-to-point) voice and data communications. Future NS/EP telecommunication requirements are expected to include requirements for high-speed data and video communications.

TABLE 1: Functional Requirements for NS/EP Telecommunications Service

VOICEBAND SERVICE	The service must provide voiceband service in support of Presidential communications.
INTEROPERABILITY	The service must interoperate with and use the resources of selected other government or private facilities, systems, and networks through the application of standards.
SURVIVABILITY/ ENDURABILITY	The service must provide for the interconnection of surviving users under a broad range of circumstances from widespread damage from natural or manmade disaster up to and including nuclear war.
INTERNATIONAL INTERFACE	The service must provide access to and egress from international service.
NATIONWIDE COVERAGE	The service must provide readily available nationwide coverage to support national security leadership and intra/interagency emergency operations.
INTRA/INTERAGENCY EMERGENCY OPERATIONS	Common user service must provide NS/EP traffic with priority service.

Source: White House Memorandum dated October 15, 1992

4.1.2 Public Switched Networks

The PSN usually refers to public circuit-switched telephone networks. As used in this report, the PSN also includes public packet-switched data networks. Circuit-switching is the dominant technology for both voice and data communications. Communications using a circuit-switched network involve three phases: circuit establishment, information transfer, and circuit disconnect. The connection path is established on an end-to-end basis before information is exchanged.

Public circuit-switched networks primarily comprise the networks of the local exchange carriers (LEC) and interexchange carriers (IEC). As a result of the 1982 Modified Final Judgment, in which AT&T agreed to divest itself of the Bell Operating Companies, the United States was divided into local access and transport areas (LATA). The LECs provide intra-LATA service and the IECs provide inter-LATA service. There are more than 1,000 LECs in the United States. The largest LECs are owned by the Regional Bell Operating Companies and GTE Corporation. AT&T, MCI, and Sprint account for approximately 90 percent of the inter-LATA telecommunications market.

Figure 3 shows the basic topology of the public telephone network. A subscriber is connected by a local loop to an LEC end office. End offices are connected to IEC points of presence, either directly or through LEC access tandem switches, which aggregate inter-LATA traffic. IEC points of presence may or may not be collocated with IEC switches. The AT&T and Sprint networks are largely nonhierarchical. The MCI network is hierarchical, but includes many high-usage trunks connecting switches at the lowest level.

Public circuit-switched networks also include cellular networks. Since it began in the early 1980s, the cellular telephone industry has grown substantially. Today, there are more than 9 million cellular telephone subscribers in the United States (Wheeler 1992). The basic topology of a cellular system is shown in Figure 4. The capabilities of cellular systems are growing as a result of the application of modern switching, signaling, and transmission technologies and the transition to digital radio technology. Wireless communications will expand further as proposed mobile satellite services and personal communications services become available. Cellular telephone systems and other wireless networks are included in this description of the PSN because the NCS plans to use these systems to increase the robustness of the PSN for NS/EP telecommunications.

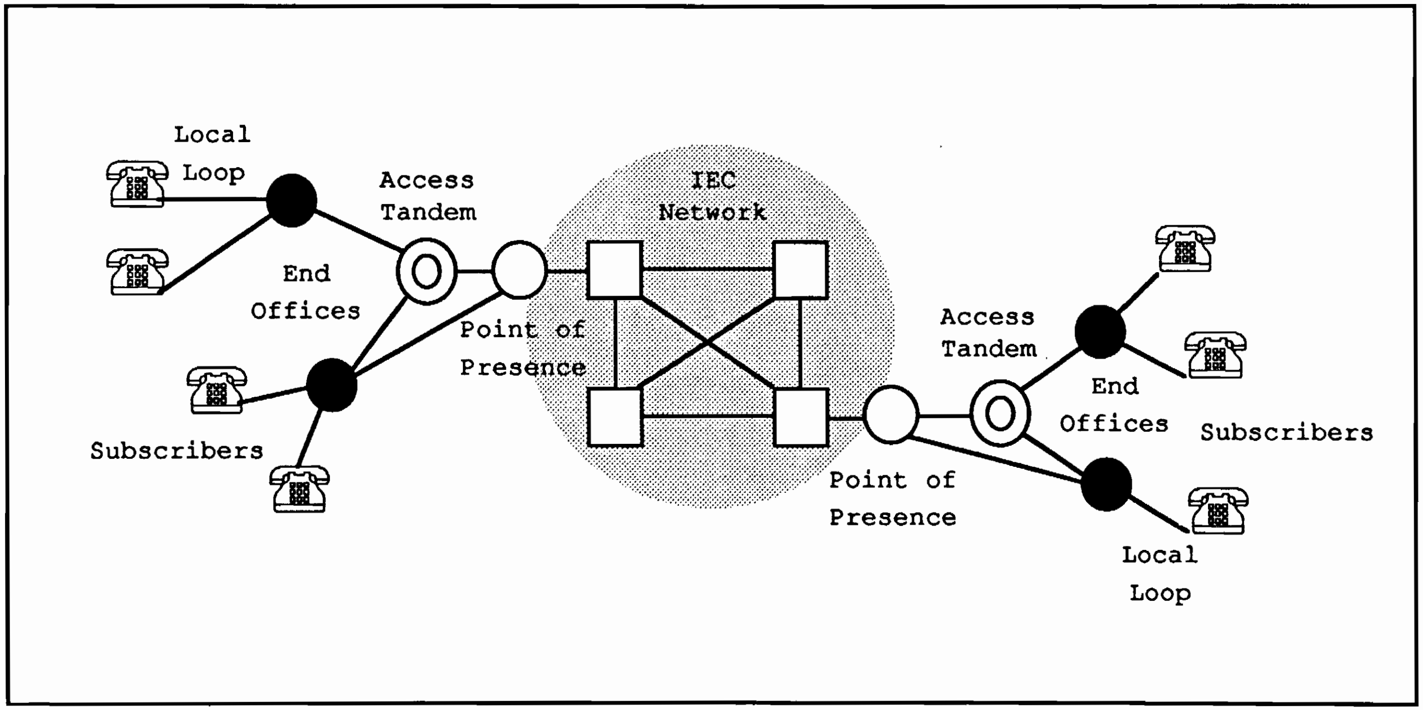


FIGURE 3: Public Telephone Network Topology

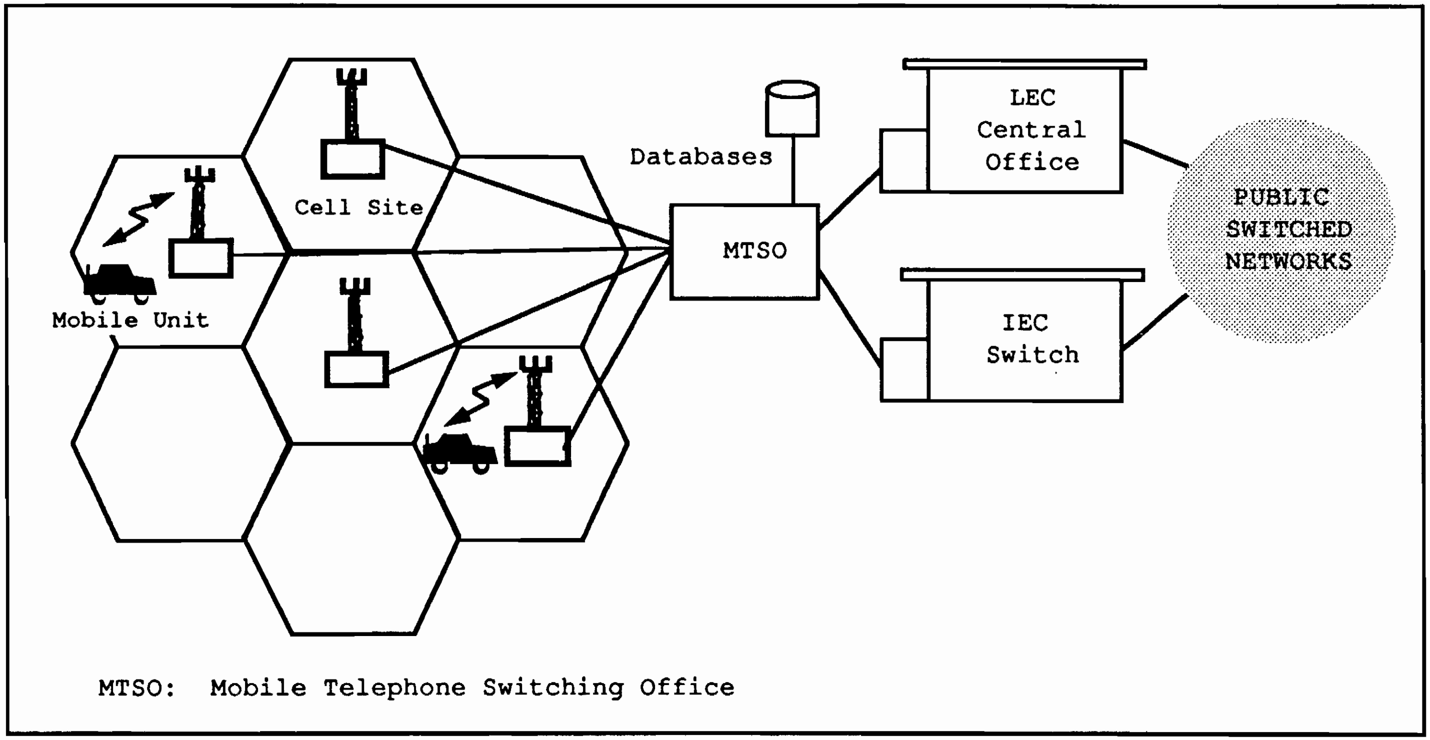


FIGURE 4: Cellular Network Topology

Packet-switched network technology developed in the early 1970s because circuit-switched networks can be inefficient for data communications. In a packet-switched network, data are transmitted in short packets. Each packet contains a portion of the user's data and some control information. The control information is used by the network to route the packet through the network. At each network node, a packet is received, stored briefly, and sent to the next node. Packet-switched networks use two approaches for sending the packets of a single message, connectionless service and connection-oriented service. For connectionless service, also called datagram service, each packet is routed independently. For connection-oriented service, or virtual circuit service, a route is established before data is transferred, and all of the packets follow the same route through the network.

The basic functions of any telecommunications network are switching, signaling, and transmission. The switching function includes connecting customers or routing data packets over appropriate transmission paths. The signaling function involves the supply and interpretation of the control and supervisory signals needed to perform this operation. The transmission function refers to the transfer of information between customers and the transmission of signaling information. Transmission media provide the physical spans over which logical connections (i.e., trunks) are established. Examples of transmission media are optical fiber, microwave radio, and coaxial cable.

The LECs and IECs are transitioning to Signaling System 7, a common-channel signaling system in which signaling instructions are transmitted over a separate packet-switched network. The basic functions of Signaling System 7 are performed by three types of signaling elements:

- Signal Transfer Points—Packet switches that route signaling messages within the signaling network
- Service Control Points—Network elements that interface with the signal transfer points and contain processors and databases used to provide advanced network services
- Service Switching Points—Network elements that interface with the carrier's switching office and the signaling network and act as the point of origin and destination for signaling messages.

The carriers have network management systems to provide real-time monitoring and control of the call-carrying capacity of the network. Network management refers to "those functions and controls that keep the network operating near maximum efficiency (as defined by completed messages per unit time) when unusual traffic patterns or equipment failures would otherwise cause network congestion or inefficiency" (AT&T Bell Laboratories 1983).

The PSN is evolving to an Integrated Services Digital Network (ISDN). The primary goal of ISDN is to integrate voice and nonvoice services. ISDN requires end-to-end digital connectivity and common-channel signaling. The customer's ISDN terminal will interface to an ISDN exchange (i.e., an end office that supports the ISDN interface). Initially, the ISDN exchange will connect to public circuit-switched networks, packet-switched networks, and the common-channel signaling network. Eventually, these networks will become one integrated ISDN transport network (Tanenbaum 1989).

4.1.3 Network Robustness Framework

Another way of describing networks is to use the network framework defined by the Technical Subcommittee T1A1.2 of the American National Standards Institute (ANSI). This subcommittee recently completed a draft report on network survivability performance (ANSI 1992). The draft report provides information on techniques for improving network survivability. The ANSI subcommittee's definition of survivability is similar to the definition of robustness used in this report. In its report, ANSI introduced a four-layer network framework to provide a common structure and terminology for discussing network survivability techniques. The ANSI-defined network framework includes a physical layer, a system layer, a logical layer, and a service layer.

Booz•Allen & Hamilton commented on the draft ANSI report and developed a modified framework, as shown in Table 2. This modified framework is referred to as the network robustness framework in the remainder of this report. The NCS is using the modified framework in its architecture development efforts. This framework is referred to in the discussion of network robustness and capability indicators. It is important to note that the physical components of the network exist at the facility layer. However, the functions of particular network components are associated with the higher levels of the framework. For example, network switches are housed in physical structures at the facility layer, but the service layer depends on the switching function.

TABLE 2: Network Robustness Framework

LAYER	COMPONENTS PROVIDING LAYER FUNCTIONS*	FUNCTION	ROBUSTNESS ROLE	ROBUSTNESS TECHNIQUES*
4 SERVICE	Equipment: Switches, Servers, Network Controllers Protocols/Information Processed: File Attributes, Data Content, Network Management Protocols	Provide user-to-user information transfer services and network management capabilities.	Support service and network access control, detect and adjust to network reconfigurations, monitor network status.	Redundant/distributed signaling, service priorities, information handling protocols (e.g., retransmission), network management controls.
3 LOGICAL	Equipment: Channel banks, Digital Cross-Connect Systems, Multiplexers Protocols/Information Processed: Network Addresses, Contention, Bandwidth Allocation	Define/manage the routing of information across the network and manage link capacity utilization.	Support reconfiguration of network assets and/or changes in routing patterns, and modify user-based demands for bandwidth.	Adaptive/dynamic routing, adaptive/dynamic bandwidth allocation.
2 SYSTEM	Equipment: Channel Service Units, Earth Stations, Base Stations Protocols/Information Processed: Synchronization, Framing	Supply signals, which enter a link or channel, and accept signals after transmission over a link or channel.	Support reliable node-to-node connectivity and the reliable transmission of information between network components.	Automatic cutover systems, excess capacity, spread spectrum transmission, coding, error correction.
1 FACILITY	Equipment: Buildings, Conduits, Power Systems Protocols/Information Processed: None	Provide the physical operating environment and information transmission bearer services.	Provide physical and electromagnetic protection of network assets.	Hardened/secure facilities, backup power systems, shielding, manual intervention, physical span diversity, transmission media diversity, fault detection systems.

*The contents of this column are examples and are not meant to be exhaustive listings.

4.1.4 Enhancement Programs and Initiatives

The NCS is revising its methodology for analyzing the costs and benefits (i.e., capability improvements) of the NLP. The NCS is also developing a methodology for analyzing the costs and benefits of proposed Enhanced Call Completion (ECC) features. The capability indicators described later in this report could be used by the NCS for these two efforts. The following paragraphs describe the NLP and the proposed ECC features. The NCS recognizes that there is some overlap between NLP enhancements and proposed ECC features.

National Level NS/EP Telecommunications Program. The NLP includes programs that are designed to provide a robust information transfer capability and are expected to result in the significant nationwide enhancement of existing PSN services. The NLP comprises three component programs: Government Emergency Telecommunications Service (GETS), Commercial Network Survivability (CNS), and Commercial SATCOM Interconnectivity (CSI).

GETS is planned to provide a nationwide capability for switched voice and voiceband data communications by exploiting the facilities of commercial and selected Government networks. When fully implemented, GETS will be accessible throughout the United States. NS/EP telecommunication users will access the service using a special number and access control procedure.

Components of GETS include priority treatment capabilities, routing enhancements, interoperability with selected Government networks, and a survivable signaling network. GETS priority treatment will be provided by the use of expansive and protective network management controls to aid call completion in a congested network. The NCS has already implemented a robust nonhierarchical routing capability in the AT&T network to provide additional routing options for NS/EP traffic. This routing capability may be replaced by a modified version of AT&T's real-time network routing service. The NCS is also considering enhanced routing in other IEC networks and in LEC networks. The GETS architecture will allow interoperability with the Federal Telecommunications System 2000 and the Defense Information Systems Network. The NCS has implemented a survivable common-channel signaling network in the AT&T network to control the establishment and teardown of NS/EP calls. In addition, GETS will use the current and planned CNS and CSI enhancements described in the following paragraphs.

The **CNS program** enhances the connectivity of the access and egress portions of an NS/EP call. Several fixed network augmentations have been implemented to increase the number and diversity of connections between the LEC and IEC networks. The CNS program has also tested the use of the tactical radio communications equipment of the National Guard to restore PSN connectivity. Future CNS enhancements may capitalize on commercially-offered disaster recovery services, intelligent network services, the private networks of telecommunication service providers, cellular network services, and personal communications services. For example, the Office of the Manager, NCS, is studying the feasibility of acquiring priority services in cellular networks.

Another initiative related to the CNS program is the National Transportable Telecommunications Capability. The NCS leases a transportable system that uses cellular and Ku-band satellite technology. This system can be deployed temporarily to restore communications to a local community of Government users. The system was recently deployed in Florida to restore some of the communications disrupted by Hurricane Andrew.

The **CSI program** uses commercial C-band satellites to enhance the connectivity of the IEC networks during national emergencies. The CSI network consists of almost 20 CSI earth stations, leased circuits between earth stations and PSN switches, and two telemetry, tracking, and control (TT&C) facilities that allow interoperability within the two commercial satellite families. These CSI network elements provide a standby backup capability if terrestrial connectivity is lost.

Enhanced Call Completion Features. The National Security Telecommunications Advisory Committee (NSTAC), which is composed of representatives of the telecommunications industry, advises the President on issues relating to national security telecommunications. An NSTAC task force recently completed a report on ECC features (NSTAC ECC Task Force 1992). These features, which include current and future PSN capabilities, are defined in Table 3. The NCS must analyze the potential costs and benefits of these features to develop a ranking of ECC features. One or more of the capability indicators developed in this project could be used by the NCS to analyze the benefits of the proposed ECC features.

4.1.5 Stress Conditions

Network stress can be grouped into damage effects and traffic congestion. Traffic congestion can result from increased demand or decreased capacity. Damage and congestion effects may be interrelated. For example, loss of a direct link between two network nodes can result in

TABLE 3: Enhanced Call Completion Features

FEATURE	DEFINITION
High Probability of Completion (HPC) Service	Proposed standard to use Signaling System 7 message format to identify NS/EP calls.
Special Application of or Exemption from Network Management Controls	Application of expansive controls or exemption from protective controls to provide priority treatment of NS/EP calls.
Enhanced Alternate Routing in IEC networks	Ability of an IEC network to select alternate paths when the primary route is congested or out of service.
PSN Partitioning	Restriction of access to some switched facilities to provide NS/EP users with enhanced network services.
Presubscription Override	Permits a user to select an IEC carrier on a call-by-call basis.
Automatic Call Rerouting	Automatic capability at LEC access tandem to select alternate IEC carriers in order predetermined by the subscriber.
Trunk Queuing	Trunk congestion control feature that enables selected calls to be held in a queue until an outgoing trunk is available.
Dynamic Trunk Reservation	Protective trunk congestion control that dynamically reserves trunk capacity for NS/EP traffic.
Trunk Subgrouping	Protective trunk congestion control that restricts access to defined trunk subgroup so that subgroup is available for NS/EP calls.
Off-Hook Trunk Waiting	Centrex-based capability that allows an authorized user meeting an all-routes-busy condition to wait off-hook for an idle trunk.
Priority Dial Tone	Service arrangement that ensures small number of subscriber lines priority dial tone during periods of PSN overload.
Enhanced Alternate Routing in LEC Networks	Ability of a LEC network to select alternate paths when the primary route is congested or out of service.
LEC Bypass	Connectivity arrangement that provides bypass of the LEC end office and a direct connection to the IEC network.

TABLE 3: Enhanced Call Completion Features (Continued)

FEATURE	DEFINITION
Diverse Routing in LEC Networks	Survivability feature in which two or more circuits serving the same facility are routed over physically diverse paths.
Diverse PSN Access and Egress from Cellular Systems	Feature allowing direct access and egress connectivity between the mobile telephone switching office and LEC or IEC switches.
Mobile Subscriber Priority Service	Service that enables selected users to receive priority access and transport in mobile telephone (i.e., cellular) networks.
Position Locating/ Tracking in Cellular Systems	Ability to locate and connect a call to a mobile telephone user automatically whether user is in his/her home network or roaming.
Avoidance Routing	Special routing arrangement that allows selected circuits to be routed over paths that avoid known or possible problem areas.
Dual Hosting (LEC Networks)	Arrangement where a lower level switch in network hierarchy connects to two higher level switches in the same network.
Dual Homing (LEC and IEC Networks)	Similar to dual hosting, but implies connections to physically diverse switching centers.
Very Small Aperture Terminal (VSAT) Satellite Service	Capability that enables user to employ VSAT (antenna from 1.2 to 3.6 meters in diameter) to access PSN via private satellite network.
Mobile Satellite Communications (MSAT)	Capability that enables user with mobile or portable satellite terminal to communicate within MSAT system or access PSN gateway.
Multilevel Precedence and Preemption	Capability to handle traffic at multiple precedence levels and preempt low precedence calls to complete high precedence calls.

increased congestion on alternate routes. This project emphasizes measures of network robustness against damage or failure effects. Damage or failure effects (i.e., stress conditions) can range from a single component failure with no effect on service to a total service outage.

The NCS is responsible for developing an NS/EP telecommunications capability for a wide range of stress conditions. Therefore, the NCS is concerned with the threats to a network that can result in stress conditions. These threats may be intentional, such as a terrorist attack on critical network facilities, or unintentional, such as an accidental cable cut. Threats to the network generally fall into three categories: natural threats (e.g., earthquakes, floods), technological and manmade threats (e.g., cable cut, bug in signaling system software), and national security threats (e.g., terrorist attack, nuclear attack). Figure 5 displays a spectrum of threats that can affect the functioning of telecommunication networks. The NCS must consider multiple threats and their predicted effects on the network in its analyses of the PSN with and without enhancements.

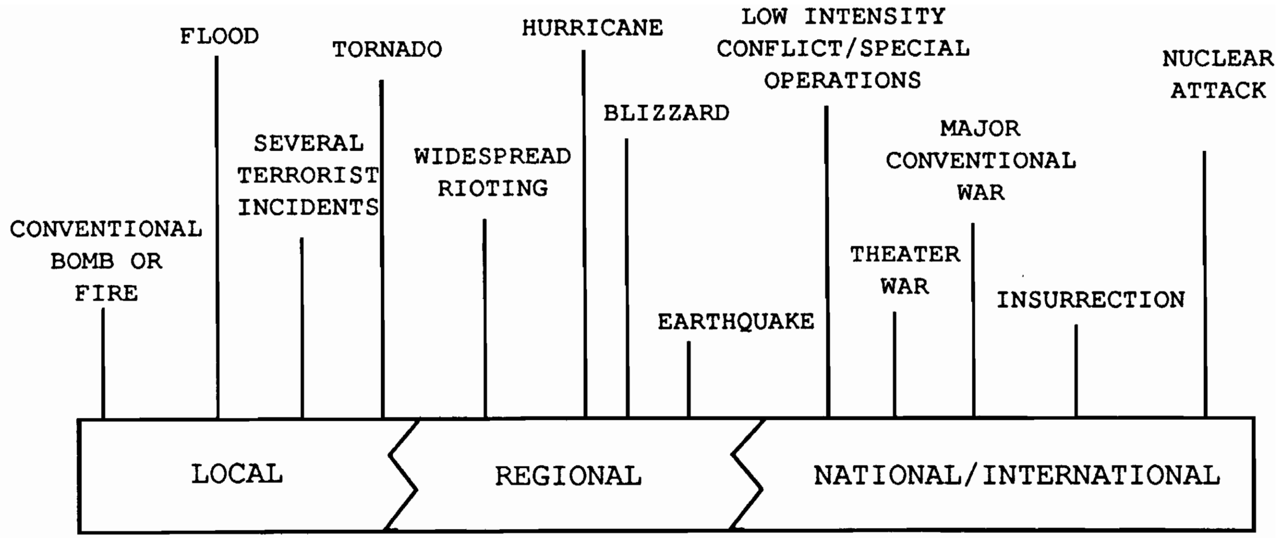


FIGURE 5: Spectrum of Threats

4.2 NETWORK ROBUSTNESS

For the purposes of this project, **network robustness** is defined as the capability of a network to maintain an acceptable level of service during stress conditions or to restore an acceptable level of service soon after network stress has occurred. The determination of an "acceptable level of service" depends on the specific needs of the users and the type of network stress. For example, NS/EP users may consider a call completion probability of 50 percent to be acceptable following a large-scale nuclear attack on the United States. However, a call completion probability of 90 percent may be considered unacceptable after an unintentional software failure in a signaling network. The interpretation of "soon" with respect to service restoral is also dependent on specific user needs and the type of stress on the network.

The definition of robustness used in this project is similar to definitions found in technical literature. A report on signaling networks prepared by AT&T for the NCS defined robustness as "the ability to provide continued service after severe physical damage" (AT&T 1991). A dictionary of communications terms defined system robustness as the "measure or extent of system resilience" where system resilience is defined as "the ability of a system, such as a computer, communication, data processing, or weapon system, to continue to function despite the existence of faults in its component subsystems or parts" (Weik 1989). An article on the design of a worldwide intelligent network states that "a robust network is one which responds in near real time to a network failure or load shift, and continues to provide connections to customers with essentially no perceived interruption of service" (Ash et al. 1989). An article on the experimental design of robust systems defined robust systems as "systems that not only satisfy performance criteria, but also are not sensitive to uncontrollable environmental conditions or *noise* in the system's environment" (Wild and Pignatiello 1991).

Several authors define **survivability** synonymously with robustness. For example, a paper presented at a 1988 communications conference defines survivability as "the ability of a network to provide an acceptable but probably reduced level of performance under failure conditions" (McGorman 1988). The draft ANSI report defines network survivability as "the ability of a network to maintain or restore an acceptable level of performance during failure conditions by applying various restoral techniques" (ANSI 1992).

The concept of network robustness, as defined in this report, requires judgment from the decision-maker(s). As mentioned earlier, robustness depends on the interpretation of "acceptable level of service" and "stress conditions." Robustness is not measured directly, but rather it is based on capability indicators for several network characteristics and the judgment of the decision-maker(s). Network characteristics related to robustness are listed and discussed below:

- Connectivity
- Physical diversity
- Restorability
- Accessibility
- Endurability
- Survivability.

These characteristics relate to the inherent capability of the PSN to operate during and after network stress. NCS-defined network enhancements should affect one or more of these characteristics.

4.2.1 Connectivity

Connectivity relates to the logical layer of the network framework presented in Section 4.1.3. **Connectivity** is defined as follows: Point A is *connected* to point B if traffic from point A can be delivered to point B using the topology and routing rules of the network. Note that this definition allows for asymmetric connectivity. Because of routing rules in a particular network, some damage patterns could destroy connectivity from A to B but not from B to A.

Connectivity can be defined between various points in the network. For example, one can examine connectivity between LEC end offices or between IEC switches. Connectivity under stress conditions can be compared to connectivity under perfect conditions. Connectivity indicators are an important indication of network robustness. According to an AT&T report on signaling network performance, "a network that is more robust than another is more likely, after damage, to have a connection between any two remaining end points of the network" (AT&T 1991).

4.2.2 Physical Diversity

Physical diversity can be defined as the degree to which physically separate and distinct transmission facilities are used to form a connection between two nodes. Physical diversity applies to the underlying physical transmission network. This corresponds to the first two layers of the network framework, the facility and system layers. However, if routing constraints are considered in determining physical diversity, then physical diversity also applies to the logical layer of the network framework. Physically diverse components and links support diversity in the logical trunk groups connecting switches and the signaling paths in the signaling network. Physical diversity is measured on a point-pair basis (i.e., physical diversity is measured between any two network nodes).

4.2.3 Restorability

Restorability and maintainability of network components and services are related concepts. **Maintainability** is defined as "the ability of an item under stated conditions of use, to be retained in, or restored to, a state in which it can perform a required function" (Brush and Marlow 1990). Maintainability is also described as the general ease of maintaining a system (Eisner 1988).

Restorability is defined as the ability of a system to be restored, automatically or through manual intervention, to its normal operating state. Restorability encompasses the part of maintainability relating to the ability of a component or system to be restored to a state in which it can perform a required function. It applies to all layers of the network robustness framework. Restorability can be evaluated with respect to physical components, transmission links, connectivity, and services. The other part of maintainability (i.e., the ability to retain an item in a state in which it can perform a required function) is not part of restorability.

Restorability is a particularly important concept to the NCS. Generally, NS/EP telecommunication users do not require uninterruptible service. However, an objective of the NCS is to develop and implement techniques for restoring NS/EP telecommunications as quickly as possible. For example, the NCS developed the Telecommunications Service Priority System to allow service providers to provision and restore NS/EP telecommunication services on a priority basis.

4.2.4 Accessibility

Accessibility is conceptually similar to reliability and availability. The International Telegraph and Telephone Consultative Committee (CCITT) defines several accessibility terms. **Service accessibility** is defined as "the ability of a service to be obtained, within specified tolerances and other given conditions, when requested by the user" (CCITT 1985).

The CCITT also defines the term **accessibility of connection establishment.** This term refers to "the probability that a switched connection can be established, within specified transmission tolerances, to the correct destination, within a given time interval, when requested by the user" (CCITT 1985). Accessibility depends on the connectivity of the logical layer, the operation of switching and network control systems to establish connections at the service layer, and user traffic requirements. Although accessibility depends on the connectivity of the logical layer, it is a characteristic of the service layer of the network framework.

4.2.5 Endurability

Endurability refers to the ability of a communications network to operate without commercial power by using uninterruptible power supplies, backup batteries, and generators during failures. This definition is consistent with the definition of endurability contained in the draft ANSI report on network survivability performance. The NCS has been studying the dependence of the telecommunications infrastructure on commercial power. Depending on the type of stress condition (e.g., impact of a terrorist attack or natural disaster), undamaged telecommunication systems may need to operate without commercial power.

The level of power reserves supporting network components affects the ability of a network to maintain an acceptable level of service under stress conditions. In other words, endurability contributes to network robustness. Many threats to the network, such as hurricanes and earthquakes, may not damage telecommunication facilities, but they may result in the loss of commercial power.

Endurability is a characteristic of the facility layer of the network framework. As defined in Section 4.1.3, backup power systems are components of the facility layer.

The concept of endurability could be expanded to include other aspects of network support. For example, the endurability of the network could be analyzed based on the assumption that staffing is unavailable. Under severe stress conditions, a switching office may have to operate unattended for an extended period. The endurability measures defined in Section 4.3 relate to the operation of the network when commercial power is unavailable.

4.2.6 Survivability

Survivability is defined as the capability of network assets and services to still be functioning following stress on the network. Network stress that results in component failures or physical damage affects survivability. Survivability is another characteristic of network robustness. It is related to other network characteristics. For example, physical assets must survive to provide connectivity between two points. Survivability must be considered before capability indicators for other robustness characteristics can be calculated. Some of the other characteristics, such as connectivity and physical diversity can be analyzed for networks under normal operating conditions. However, survivability is not relevant unless a stress on the network has occurred.

Survivability applies to all layers of the network framework. The survivability indicators defined in this project specifically address the facility and service layers. Connectivity and physical diversity indicators provide information on survivability at the system and logical layers. At the service level, assets needed to provide a particular service can be defined. These assets must survive in order to support that service. For example, toll-free calling service (800 service) requires information from a central database. This database must survive in order to maintain the service under stress conditions.

In comparing networks, one network can be considered more survivable than another network if a higher percentage of its physical assets survive under stress conditions. Other percentage relations are possible. For instance, point-pair connectivity could be used to order the survivability of networks. Survivability at the service level requires a high percentage of surviving physical assets and the necessary combination of surviving assets.

4.2.7 Network Robustness Discussion

The characteristics defined above influence the capability of a network to maintain or restore an acceptable level of service under stress conditions. These characteristics are not all independent. For example, accessibility is dependent on connectivity. If logical connectivity does not exist between two users, a connection cannot be established between them. Another example is the relationship between physical diversity and restorability. If the primary route between two nodes fails, a physically diverse route could be used to restore service between these nodes. A network management control may need to be invoked to allow the use of the alternate route. As mentioned, survivability influences the values of capability indicators for other characteristics.

Collectively, the six robustness characteristics provide an understanding of the capability of a network to maintain or restore service under stress conditions. Some of these characteristics specifically address the capability to maintain service, others relate to the capability to restore service, and others apply to maintaining and restoring service. For example, network connectivity and endurability contribute to the capability of the network to maintain an acceptable level of service. Restorability refers to the capability to restore service quickly. Network components must survive under stress to maintain service and to be used in the restoration phase.

Unlike most of the other robustness characteristics, accessibility indicators can be used to measure actual system performance. However, for this project, accessibility indicators are proposed to predict the capability of a network under stress conditions. Robustness depends on maintenance or restoral of an acceptable level of service. Accessibility is the characteristic that relates to the level of service provided by a network.

Network robustness can be evaluated in the context of the four-layer network framework presented in Section 4.1.3. Figure 6 maps the robustness characteristics against the network layers, showing which characteristics are relevant to each layer. Some of the characteristics are associated with a single network layer, while others relate to multiple

NETWORK LAYER ROBUSTNESS CHARACTERISTIC	1 Facility	2 System	3 Logical	4 Service
Connectivity			●	
Physical Diversity	●	●	●	
Restorability	●	●	●	●
Accessibility				●
Endurability	●			
Survivability	●	●	●	●

FIGURE 6: Robustness Characteristics Versus Network Framework Layers

layers. Capability indicators can be defined based on the characteristic and the relevant network layer(s).

The robustness characteristics should be traceable to system requirements. The national policy guidance discussed in Section 4.1.1 directs the NCS to ensure that the telecommunications infrastructure incorporates the following characteristics: connectivity, redundancy, mobility, interoperability, restorability, hardness, security, survivability, endurability, international interface, nationwide coverage, and intra/interagency emergency operations.

Some of these required characteristics fall outside the scope of network robustness, such as mobility, interoperability, security, international interface, and nationwide coverage. Although these characteristics are not directly related to robustness, they are important effectiveness factors to consider in analyses. The robustness characteristics defined in this project include connectivity, restorability, survivability, and endurability. The concept of redundancy is related to accessibility. A network architecture that incorporates redundant elements is more likely to continue to complete calls if individual elements fail. In addition, accessibility is related to the requirement to support intra/interagency emergency operations. The intra/interagency emergency operations requirement is defined as the ability to provide preferential treatment of NS/EP traffic. Accessibility refers to the probability of completing a call. This probability is increased if NS/EP calls receive priority treatment in a stressed network.

Reliability, availability, and maintainability are important effectiveness criteria in systems design and development. Reliability and availability are usually defined based on ideal or normal operating conditions. Although robustness refers to network performance under stress conditions, the general concepts of reliability and availability are encompassed by the six robustness characteristics discussed in this section. In particular, accessibility is closely tied to reliability and availability. A speaker at a recent conference stated that service reliability means that "a service works the way a customer wants it to work when the customer wants it" (Ripa 1992). This definition is equivalent to accessibility, where accessibility is the ability of a service to be obtained, or a connection to be established, when requested by the user. The term accessibility is used in this report instead of reliability to avoid confusion with other definitions of reliability that may not apply to a telecommunications network. The concept of maintainability is also incorporated in the set of robustness characteristics. Characteristics such as connectivity, physical diversity, and endurability relate to the ability of the network to be retained in a state in which it can perform its required function (i.e., establish connections and/or transfer information). The other aspect of maintainability, which is the ability to restore a system to a state in which it can perform a required function, is reflected in the restorability characteristic.

4.3 CAPABILITY INDICATORS

Capability indicators should be quantifiable and they should relate to the robustness characteristics discussed in Section 4.2. In addition, they should be derived from system requirements. The NCS is developing and implementing enhancements to the PSN to support NS/EP telecommunication requirements. The NCS must ensure that these requirements can be met under a range of stress conditions. Network robustness, which refers to the capability of the PSN to provide service under stress conditions, is a key system effectiveness criteria. Although network robustness is not directly measurable, capability indicators can be defined for the network characteristics that affect overall network robustness.

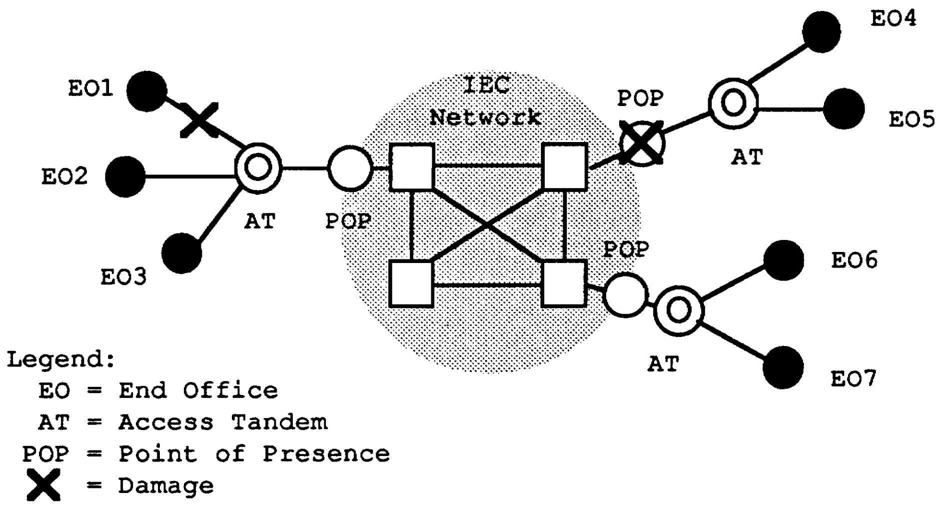
This section defines capability indicators for each of the six characteristics introduced in Section 4.2. A qualitative evaluation of each capability indicator is also included. This evaluation is based on the relevance of the indicator to NCS analysis requirements, conceptual simplicity, complexity or difficulty of determining indicator values from network models, and sensitivity of the indicator to specific types of network stress.

4.3.1 Connectivity

Connectivity is a characteristic of the logical layer of the network robustness framework. It relates to the existence of logical connections between network nodes (i.e., connections that can be established according to the topology and routing rules of the network). The network nodes may be connected directly or with links in tandem.

Relative Connectivity. AT&T defined relative connectivity as an indicator of network robustness in a report to the NCS on the Survivable Signaling Network (AT&T 1991). Relative connectivity can be defined as the ratio of actual node-pairs connected to total number of node-pairs. For a network under stress, relative connectivity can be defined as the ratio of surviving and connected node-pairs to the total number of surviving node-pairs. The relative connectivity of a network or group of networks can be determined at several levels. For example, relative connectivity can be calculated on a user-to-user basis, an access tandem-to-access tandem basis, or an IEC switch-to-IEC switch basis. It can also be calculated for signaling nodes in a common-channel signaling network (e.g., service switching point-to-service switching point) or packet switches in a public packet-switched network. An example calculation of relative end office-to-end office connectivity is shown in Figure 7.

Evaluation of Relative Connectivity. Relative connectivity indicators are particularly relevant in the analysis of NCS programs and initiatives. These indicators apply to any type of network and many existing and proposed Government-funded enhancements affect connectivity, such as CSI and robust nonhierarchical routing. The concept of relative connectivity is simple if the analysis audience has a basic understanding of the topology of the PSN. The NCS has used relative connectivity indicators in previous analyses. Therefore, NCS decision-makers are familiar with these indicators. The NCS has established procedures for modeling the PSN to generate values of relative connectivity. PSN data to support these indicators are also available. Relative connectivity can be determined for a range of stress conditions, from an isolated node or link failure to a



Example Calculation of Relative EO-to-EO Connectivity

Total Number of Surviving EO Pairs = [n(n-1)]/2 = 7*6/2 = 21

Connected EO Pairs:
EO2-EO3
EO2-EO6
EO2-EO7
EO3-EO6
EO3-EO7
EO4-EO5
EO6-EO7

Number of Connected EO Pairs = 7

Relative Connectivity = 7/21 = 33.33%

FIGURE 7: Relative Connectivity

severely damaged PSN. However, relative connectivity indicators cannot be used to understand the effects of congestion on the network. If relative connectivity is calculated for a large number of node-pairs (e.g., end office-to-end office connections), it may not be useful for analyzing lower stress levels. The change in relative connectivity due to a small number of node and/or link failures may be negligible.

Mean Network Size. AT&T also defined mean network size as an indicator of network robustness in its Survivable Signaling Network report (AT&T 1991). The network size of a switch is the number of other switches to which it can connect without using an intermediate or tandem switch. The mean network size is the average network size over all switches in a network. An inoperable switch has a mean network size of 0. A disconnected but operable switch has a network size of 1. The scale of mean network size ranges from 0 to the total number of switches within a network. An advantage of this indicator over relative connectivity is that it distinguishes between a damaged and/or failed switch and a disconnected switch.

Mean network size can be calculated for an individual LEC, IEC, common-channel signaling network, or a packet-switched data network. As cellular service providers continue to interconnect the mobile telephone switching offices in multiple cellular service areas, mean network size could be used as an connectivity indicator for cellular networks. Figure 8 shows the calculation of mean network size for a network under normal operating conditions and under stress conditions.

Evaluation of Mean Network Size. Mean network size is a good indicator of the connectivity of an undamaged network. It can also be used as a connectivity indicator for a stressed network. Mean network size is relevant to NCS analysis needs because many NCS enhancements affect network connectivity. Mean network size considers the average number of switches to which an individual switch can directly connect (i.e., no links in tandem). For a network that has sustained some damage, however, there may be some key switches that allow the network to preserve relative connectivity at a much higher level than if these key switches were damaged. Because relative connectivity allows tandem switching to be considered while mean network size does not, the difference could be considerable. This situation is illustrated in Figure 9. A revised definition of mean network size, which allows a specified number of links in tandem to connect two switches, would be more useful in NCS analyses.

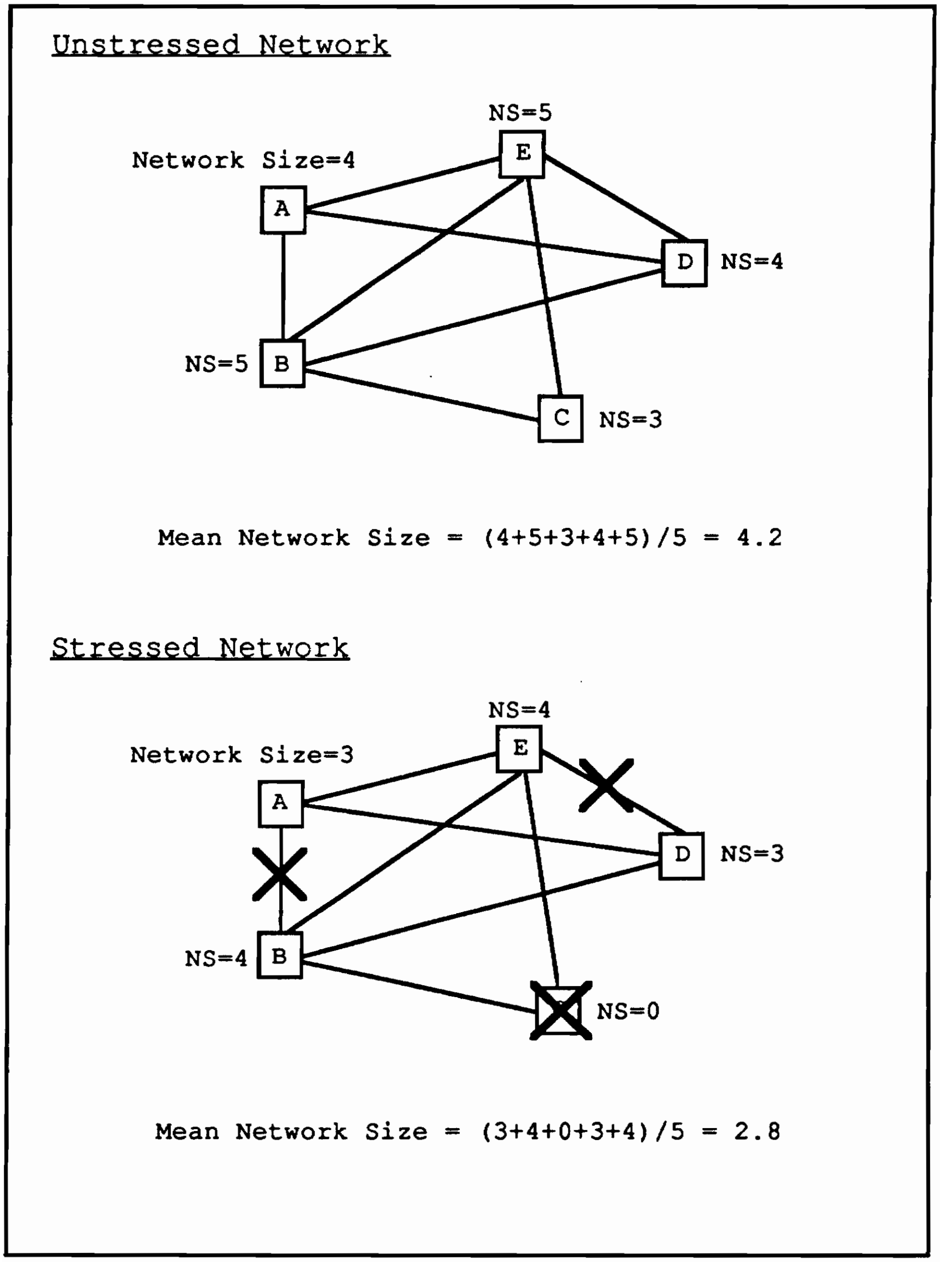
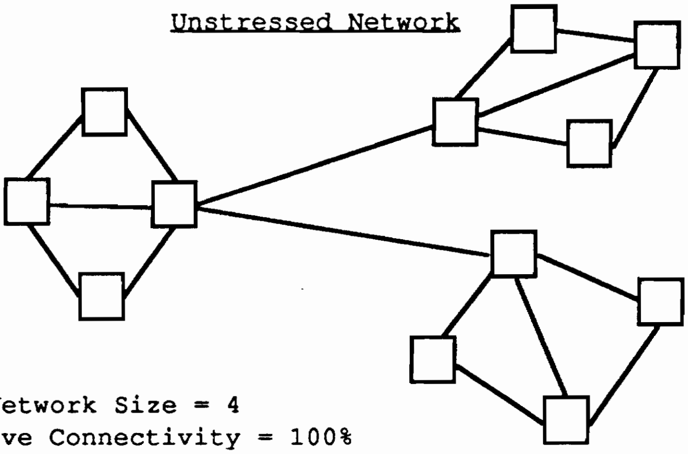


FIGURE 8: Mean Network Size

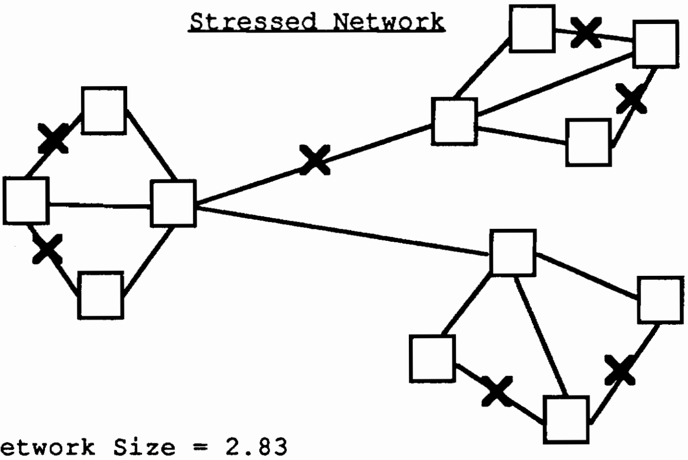
EXAMPLE: Routing rules allow 2 tandem switches.

Unstressed Network



Mean Network Size = 4
Relative Connectivity = 100%

Stressed Network



Mean Network Size = 2.83
Relative Connectivity = 0.86

Decrease in Mean Network Size = 1-2.83/4 = 29%

Decrease in Relative Connectivity = 1-0.86/1 = 14%

FIGURE 9: Comparison of Mean Network Size and Relative Connectivity

The concept of network size is straightforward and can be easily explained through examples. Given existing modeling tools and PSN data, the calculation of this indicator is feasible. Like relative connectivity, mean network size can be calculated for varying levels of stress. However, for large networks, mean network size may not be a good indicator for analyzing the connectivity of a network under low levels of stress (i.e., a few node or link failures). As with relative connectivity, the impact of a small number of failures on mean network size may be negligible. Mean network size cannot be used to analyze the effects of traffic congestion on network performance.

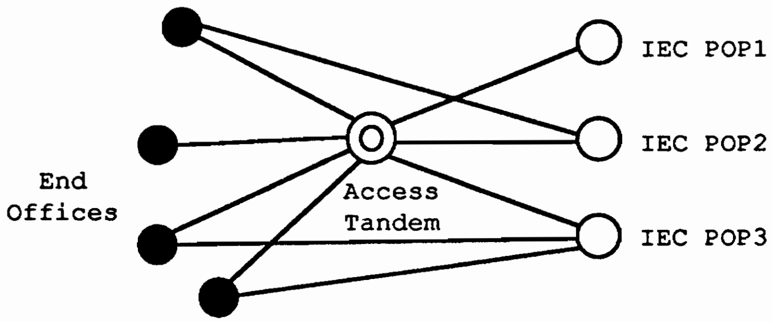
LATA Connectivity. Members of Booz•Allen & Hamilton's Telecommunications Practice recently defined LATA connectivity as an indicator of network robustness. LATA connectivity is the number of access and egress paths from end offices to IEC points of presence divided by the number of end offices in a LATA. Access and egress paths are connections from the end office through the access tandem to an IEC point of presence or high-usage trunk connections from an end office directly to an IEC point of presence. LATA connectivity can be calculated for all end offices in a LATA or for the subset of end offices serving NS/EP user locations. It can also be calculated for an unstressed or stressed network. Figure 10 contains the formulas and an

$$\text{LATA Connectivity} = \frac{\text{No. Access and Egress Paths}}{\text{No. End Offices}}$$

$$= \frac{(\text{No. EO-AT-POP conn.})(1) + (\text{No. EO-POP HU conn.})(2/3)}{\text{No. End Offices}}$$

where EO = end office
AT = access tandem
POP = point of presence
HU = high usage

Example Calculation of LATA Connectivity



$$\begin{aligned}\text{LATA Connectivity} &= [(12)(1)+(3)(2/3)]/4 \\ &= 14/4 \\ &= 3.5\end{aligned}$$

FIGURE 10: LATA Connectivity

example calculation of LATA connectivity. Note that the formula multiplies the number of high-usage connections between end offices and IEC points of presence by a two-thirds weight. This weight is based on the assumption that most high-usage trunks are not routed over paths that are physically diverse from the end office-to-access tandem-to-point of presence path.

Evaluation of LATA Connectivity. LATA connectivity is relevant to NCS analysis requirements. This indicator has already been used by the NCS to analyze how CNS augmentations improve connectivity. LATA connectivity information can be used with threat information (i.e., information on areas at risk for specific types of disruptions) to identify LATAs where enhancements are most needed. LATA connectivity is useful in evaluating alternative enhancements in LEC networks and at the interface to the IEC networks. It can also be used to identify the most effective placement of enhancements in the network.

LATA connectivity is conceptually simple and can be calculated using existing analysis tools. LATA connectivity can be calculated for a variety of stress scenarios. LATA connectivity is particularly useful in analyses of portions of the network under low levels of stress.

4.3.2 Physical Diversity

Physical diversity is the degree to which physically separate transmission facilities are used to form a communications link between two nodes. Physical diversity is a characteristic of the facility and system layers of the network robustness framework. It can also apply to the logical layer if routing rules are considered in its calculation.

Equivalent Diverse Routes. AT&T developed the equivalent diverse routes (EDR) indicator to evaluate robust nonhierarchical routing designs. The calculation of EDR is accomplished in three steps. First, calculate relative diversity by comparing the diversity of two routes connecting a node-pair. Its value ranges from 0 to 1. If two routes follow the same physical path, then relative diversity is 0. The relative diversity for two routes whose paths are completely diverse is 1. Next, determine the diversity potential of a specific route X by averaging all relative diversities that use route X within their route set. Diversity potential is also a value between 0 and 1 inclusive. Diversity potential of route X can be viewed as the amount of diversity that route X adds to the overall diversity of the route set. The EDR is the sum of the diversity potentials for all routes in the route set. EDR is less than or equal to the number of routes in the route set being examined. Figure 11 contains the formulas for the AT&T diversity indicators and includes an example calculation.

Evaluation of EDR. Although EDR is an indicator of physical diversity, a previous analysis by Booz•Allen revealed that it can produce counter-intuitive results for certain cases, such as the examples in Figure 12. In addition, EDR is more difficult to explain than connectivity measures, and currently available data are not sufficient to calculate EDR for portions of the PSN. EDR is not considered further in this project, primarily because it can produce misleading results.

P-Diversity. Professionals in Booz•Allen & Hamilton's Telecommunications Practice defined P-diversity as an indicator of the physical diversity between two network nodes. P-diversity was developed because of the problems with the EDR measure. P-diversity formulas were derived from examples where intuitive results were easily defined. Two of these examples are shown in Figure 13. P-diversity is calculated by adding the route diversities for all routes in a route set. Route diversity represents the contribution of each route to P-diversity. Its value ranges from 0 to 1. The maximum value of P-diversity is the number of routes in

$$\text{Relative Diversity (Dij)} = 1 - \frac{\text{overlap(i,j)}}{\text{ave. length(i,j)}}$$

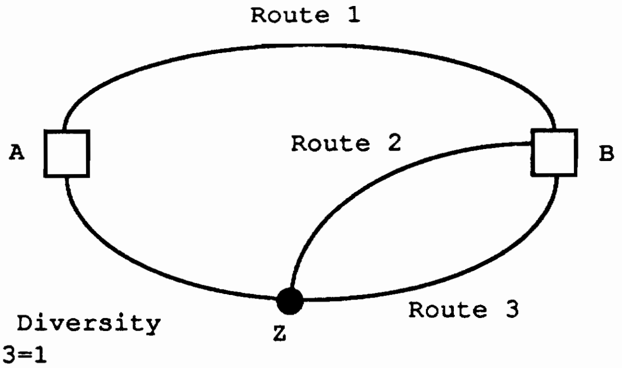
where i and j represent two routes,
overlap(i,j) is length of overlap between i and j,
and ave. length(i,j) is average length of i and j

$$\text{Diversity Potential (D.pot(i))} = \frac{\text{Sum(Dij)}}{\text{(n-1)}} \text{ for j=1 to n}$$

where n = number of routes in set

Equivalent Diverse Routes (EDR) = Sum(D.pot(i)) for i=1 to n

Example Calculation of EDR



Relative Diversity
D12=D13=1
D23=0.59

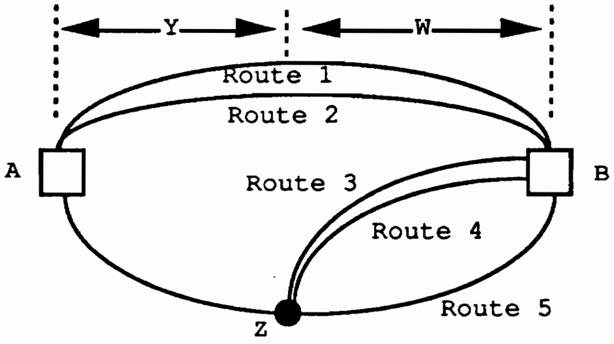
Diversity Potential
D.pot1=1
D.pot2=0.8
D.pot3=0.8

EDR=1+0.8+0.8=2.6

Route Lengths:
1 - 200 miles
2 - 250 miles
3 - 240 miles
AZ overlap - 100 miles

FIGURE 11: Equivalent Diverse Routing

EDR Example 1

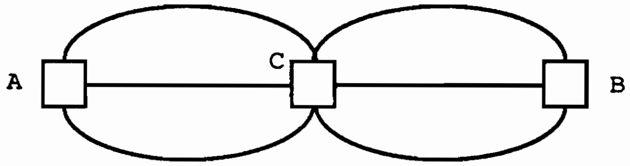


All routes are Y+W miles long.
Overlap segment AZ=Y miles.

Diversity Potential:
D.pot1=D.pot2=1
D.pot3=D.pot4=D.pot5=1-Y/[2(Y+W)]

EDR:
As Y approaches 0, EDR=5
As W approaches 0, EDR=3.5 (intuitively, EDR should be 3)

EDR Example 2



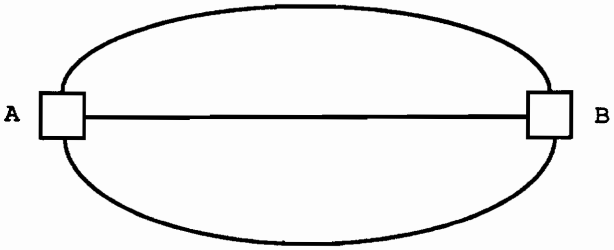
All links are length X.
Nine routes from A to B.

Diversity Potential:
D.pot1=D.pot2=...=D.pot9=0.75

EDR:
EDR=9(0.75)=6.75 (intuitively, EDR should be 3)

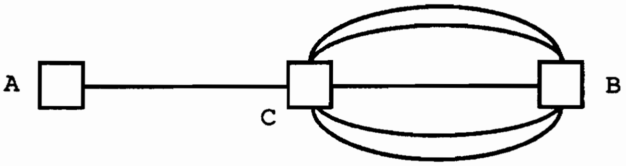
FIGURE 12: Equivalent Diverse Routing Examples

Physical Diversity Example 1



Intuitively, this transmission network has a physical diversity of 3 between A and B.

Physical Diversity Example 2



The physical diversity between A and C is 1. The physical diversity between C and B is 5. Assuming the distance from A to C is equal to the distance from C to B, then it is reasonable to assign the average of 1 and 5, namely 3, as the diversity between A and B.

FIGURE 13: Physical Diversity Examples

the route set. Formulas for route diversity and P-diversity and a sample calculation are contained in Figure 14.

Evaluation of P-Diversity. P-diversity can be calculated for node-pairs in an unstressed or stressed network. It could be used by the NCS to analyze the physical diversity between PSN nodes. For example, the NCS could average the P-diversity values for a particular set of node-pairs, such as NS/EP user location-to-access tandem node-pairs. P-diversity is a relevant indicator for NCS analyses, because the purpose of some of the current and proposed PSN enhancements is to increase physical diversity. Route diversity and P-diversity allow the NCS to compare the diversity of two or more routes within a trunk group and to rank specific routes by diversity. Analyzing P-diversity for an unstressed network provides an understanding of the number of link failures that can be tolerated before connectivity is lost between two nodes.

The formulas for P-diversity may seem complicated, but the basic concept is simple. The calculation of P-diversity requires knowledge of the physical topology of the PSN and knowledge of the route-miles of overlap. It is technically feasible to model the P-diversity of the PSN, but it is data- and computer-intensive. Currently available PSN data, particularly LEC network data, are not sufficient.

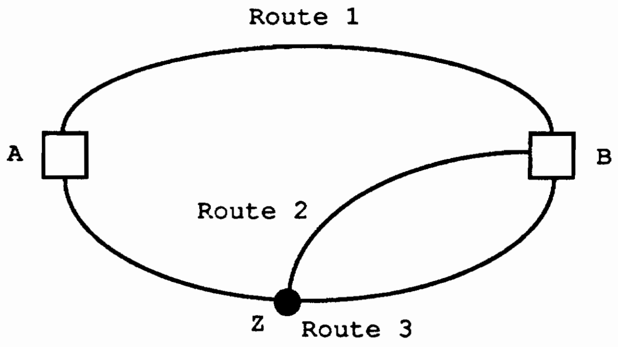
Route Diversity (Di) = 1-Sum[fj(nj-1)/nj] for j=1 to m

where i represents a route,
j = overlap,
m = number of distinct overlaps in which route i participates,
fj = length of overlap/average length of routes in overlap j,
and nj is the number of routes participating in overlap j

P-diversity = Sum(Di) for i=1 to n

where n is the number of routes

<u>Example Calculation of P-Diversity</u>



Route Diversity
D1=1
D2=1-(100/245)(1/2)=0.8
D3=1-(100/245)(1/2)=0.8

P-diversity=1+0.8+0.8=2.6

Route Lengths:
1 - 200 miles
2 - 250 miles
3 - 240 miles
AZ overlap - 100 miles

FIGURE 14: P-Diversity

accurate to support this indicator. P-diversity can be analyzed for a range of stress conditions, including low levels of network stress. However, network congestion effects will not be reflected in P-diversity values.

4.3.3 Restorability

Restorability is the ability of a system to be restored, automatically or through manual intervention, to its normal operating state. Restorability indicators can be defined for each layer of the network robustness framework.

Mean Time to Repair. Mean time to repair can be determined for individual network components at the facility layer. Mean time to repair is the expected length of time needed to repair a specific network component. It can also be averaged for a group of network components.

Evaluation of Mean Time to Repair. The repair of components is part of the restoration of the network to its normal operating state. Although this is a valid indicator of restorability, it is not particularly relevant to existing NCS analysis requirements. The NCS is not proposing methods for reducing the mean time to repair individual network components. Therefore, the value of this indicator for specific types of network components will not change if

Government-funded enhancements are implemented in the PSN. If future NCS efforts are directed toward improving component restorability, then mean time to repair would be a relevant capability indicator. The concept of mean time to repair is simple, and values for this indicator can be calculated easily. However, the NCS would have to work with the telecommunications industry to obtain data on repair times for specific network components. Different stress conditions could result in different values for mean time to repair. For example, transportation problems resulting from severe hurricanes could make it difficult for a repair person to get to a facility with damaged or failed equipment. Mean time to repair is valid for stress conditions that result in physical damage to telecommunications hardware. The concept of mean time to repair could also be expanded to include fixes to network software.

Mean Time to Restore. An indicator of restorability for the system, logical, and service layers is mean time to restore. At the system layer, mean time to restore could apply to specific direct links between nodes. Mean time to restore connectivity between two network nodes through direct links or links in tandem is a logical layer indicator. This indicator could also be calculated for an aggregate set of connections—for example, the mean time to restore connectivity between all switches in an IEC network. Mean time to restore can also apply to the service layer. The NCS could develop estimates of the mean time to restore service to NS/EP telecommunication users.

Evaluation of Mean Time to Restore. Restorability is a particularly relevant characteristic of network robustness for the NCS to consider in its analyses. The objective of the NCS is to ensure that NS/EP telecommunication requirements are met during all types of emergencies, including attacks on the United States. The NCS may not be able to guarantee uninterruptible NS/EP telecommunications service, but it must provide mechanisms for restoring NS/EP telecommunications on a priority basis (i.e., restoring NS/EP service before restoring service to other PSN users). The benefits of NCS initiatives, such as the use of transportable equipment to restore failed PSN links supporting NS/EP traffic, should be determined by estimating changes in mean time to restore.

Mean time to restore is conceptually simple. However, the determination of mean time to restore requires an analysis of historical data on network failures and outages to develop estimates of restoration times for various types of network problems. The Network Reliability Council, a Federal Communications Commission advisory committee, is currently gathering this type of information. The NCS could use the information to predict the mean time to restore transmission links, connectivity, and services in the PSN for particular stress conditions. Next, the NCS could estimate the difference in mean time to restore when enhancements are implemented in the PSN. For example, it may take a week to restore service to a customer if the end office serving the customer's location is physically damaged. However, the NCS could provide a connection to an alternate end office using National Guard tactical radio equipment within 24 hours.

Mean time to restore is applicable to all types of stress conditions. For example, the NCS could analyze the mean time to restore service to NS/EP users in a particular area after an accidental cable cut. The NCS could also analyze the mean time to restore a particular level of service after network congestion has increased the percentage of calls that are blocked in the network (i.e., not completed).

4.3.4 Accessibility

Accessibility combines the concepts of reliability and availability under stress conditions and expected NS/EP traffic. Accessibility depends on the likelihood of obtaining a service or establishing a connection within given time intervals. Accessibility depends on the connectivity of the logical layer and the functions associated with the service layer of the network robustness framework.

Call Completion Probability. Call completion probability is an indicator of accessibility for circuit-switched networks. It is defined as the probability that an NS/EP call can be completed (i.e., the probability that a switched connection can be established). It can also be viewed as the percentage of NS/EP telecommunications traffic that can be completed. Traffic from NS/EP user locations that are damaged or do not have a connection to an operable end office is ignored. Blocking probability, or grade of service, is the complement of call completion probability (i.e., blocking probability and call completion probability sum to 1). Either call completion probability or blocking probability could be used as an indicator of accessibility.

Call completion probability can be calculated by dividing the NS/EP carried load by the NS/EP offered load. The offered load is the sum of the NS/EP user requirements for undamaged locations with connectivity to a functioning end office. The carried load is a function of the NS/EP traffic, the connectivity of the network, and blocking probabilities for each segment of an NS/EP call. Call completion probability takes into account damage and congestion effects in the network. The likelihood that signaling network elements are available to establish a call can also be included in the determination of call completion probability. The network may not be able to complete some calls because of signaling network damage or failures. An example calculation of call completion probability is shown in Figure 15. Call completion probability for this example is based on the NS/EP traffic between four end offices. It assumes that the signaling network is operating properly.

Evaluation of Call Completion Probability. Call completion probability is a key capability indicator for the NCS to use in its analyses. This indicator has been used in previous analyses and decision-makers are familiar with it. However, the method of calculating call completion probability can vary depending on analysis assumptions. This variation can confuse NCS decision-makers. Call completion probability requires a significant modeling effort, but its relevance to the NCS's analysis requirements outweighs the modeling complexity. Weaknesses of this indicator stem from the assumptions that are required to calculate call completion probability. For example, assumptions must be made about NS/EP user requirements and traffic. To define NS/EP telecommunication requirements, Federal agencies must predict their critical communication needs based on hypothetical emergency scenarios. This makes it difficult to collect accurate user requirements data.

Example Calculation of Call Completion Probability

NS/EP Traffic Matrix

	EO1	EO2	EO3	EO4
EO1		10	5	0
EO2	6		4	8
EO3	8	3		4
EO4	2	5	6	

Total Offered
Traffic = 61 erlangs

PSN Connectivity Matrix

	EO1	EO2	EO3	EO4
EO1		1	0	1
EO2	1		1	0
EO3	0	1		1
EO4	1	0	1	

1–Available Connection
0–No Connection

(1-Estimated Blocking)
for each EO-pair

	EO1	EO2	EO3	EO4
EO1		0.7	0.8	0.7
EO2	0.7		0.7	0.75
EO3	0.8	0.7		0.8
EO4	0.7	0.75	0.8	

Carried NS/EP Traffic
Matrix

	EO1	EO2	EO3	EO4
EO1		7	0	0
EO2	4.2		2.8	0
EO3	0	2.1		3.2
EO4	1.4	0	4.8	

Total Carried
Traffic = 25.5 erlangs

$$\text{Call Completion Probability} = \frac{\text{Total Carried Traffic}}{\text{Total Offered Traffic}}$$

$$= 25.5/61 = 41.8\%$$

FIGURE 15: Call Completion Probability

Call completion probability can be calculated for all types of stress conditions. However, call completion probability may not be useful for measuring the effects of a low level of stress, such as one or two link failures, on a large network supporting thousands of NS/EP telecommunication line requirements. However, unlike connectivity and physical diversity indicators, call completion probability can be used to analyze the effects of network congestion.

As mentioned, blocking probability is the complement to call completion probability. The method for calculating call completion probability discussed above uses estimates of call blocking probability on specific call segments. A recent Booz•Allen analysis examined network congestion and blocking probability in more depth. For this analysis, blocking probabilities were calculated for each end office pair using each IEC network. An overall blocking probability was determined by considering the average blocking over all IECs weighted by their respective share of the total traffic.

NCS analyses of network robustness should include either call completion probability or blocking probability. It is not necessary to include both in the same analysis.

Throughput. Throughput is an accessibility indicator for data communications. It applies to packet-switched networks, including common-channel signaling networks, and circuit-switched networks. It also applies to data communications over dedicated circuits. Throughput is defined as the amount of useful and nonredundant information processed or communicated through a network during a specified period of time. Throughput is often expressed in bits per second.

Booz•Allen & Hamilton studied the throughput of packet-switched networks under stress conditions for the Defense Information Systems Agency. For this study, throughput was calculated by dividing network capacity by offered load and was expressed as a percent. The study assumed that if sufficient network capacity is available, information will be transferred correctly. Throughput was calculated for two traffic distributions, a uniform distribution and a distribution based on distance between originating and terminating switches. The modeling software used required assumptions about switch processing speed, amount of traffic offered by each node, and the allowable packet transit delay. The likelihood of packet receipt was also calculated for the study by dividing actual switch-pair connections (i.e., connections in a stressed network) by possible switch-pair connections (i.e., connections in an unstressed network). The likelihood of packet receipt is similar to relative connectivity.

Evaluation of Throughput. As NS/EP requirements for data communications increase, indicators of robustness for public packet-switched networks will become more relevant in NCS analyses. Accessibility is a characteristic of network robustness, and throughput can be used as an indicator of accessibility. Throughput can be explained easily to decision-makers, and it can be modeled easily. Because throughput is a common measure of actual system performance, most commercially-available network modeling packages can be used to calculate throughput. Throughput can be analyzed for unstressed networks and stressed networks. It is a relevant measure of network robustness at any level of stress and for any type of stress (i.e., network stress resulting from physical damage and/or traffic congestion).

4.3.5 Endurability

Endurability refers to the ability of a network to continue to provide service if commercial power is unavailable. Certain stress conditions may not directly damage telecommunication systems, but they may disrupt power to these systems.

Average Power Reserve Capacity. The endurability of a network can be defined as the average power reserve capacity for telecommunication assets. This capacity can be calculated by collecting data on the average hours of battery backup at specific sites and the average hours or days of fuel available for generators. Much of this information is already available to the NCS. Average power reserve capacity could be determined for all telecommunication assets or a subset of assets that are critical to NS/EP telecommunications. The NCS may also want to examine the backup power systems available to support customer premises equipment at NS/EP user locations. To interpret values of power reserve capacity, the NCS should have information on the expected length of time that commercial power may be unavailable for different types of stress conditions. The NCS should also have information on how easily commercial power can be restored to particular sites or how easily additional fuel can be provided.

Percentage of Network Assets with Power Reserves. In addition to the determination of the average backup capacity of network components, the NCS should examine the percentage of network assets with specified levels of power reserves. Many telecommunication systems may not have backup power capability or have a very limited backup power capability. The NCS could use the percentage of network assets with power reserves in conjunction with average power reserve capacity to develop a matrix, such as the one shown in Table 4.

TABLE 4: Power Reserves Matrix

ILLUSTRATIVE

LEVEL OF BACKUP POWER / PSN ASSET	More than 20 days	10-20 days	1-10 days	Less than 1 day
LEC Central Offices	5%	15%	75%	5%
LEC Access Tandems	5%	20%	75%	0%
LEC Fiber Regenerators	0%	5%	55%	40%
LEC Cable Repeaters	0%	5%	80%	15%
LEC Microwave Repeaters	0%	5%	85%	10%
IEC Terminals/ Junctions	10%	30%	60%	0%
IEC Switches	5%	25%	65%	5%
IEC Fiber Regenerators	0%	5%	75%	20%
IEC Cable Repeaters	5%	20%	70%	5%
IEC Microwave Repeaters	5%	20%	70%	5%

ILLUSTRATIVE

Evaluation of Endurability Indicators. Endurability is a characteristic of a robust network. The NCS does not currently have existing programs or initiatives to increase the power reserve capacity of network assets or to increase the percentage of network assets with backup power systems. However, the NCS has been working with the Department of Energy to develop a priority system for restoring commercial power and distributing fuel for generators. If the NCS continues in this endeavor, endurability indicators would be relevant indicators of the benefit of this initiative. Power restoration and fuel distribution priorities should improve the endurability of telecommunication networks if key PSN assets receive priority.

The calculation of average power reserve capacity and percentage of network assets with power reserves is extremely simple. The difficulty lies in the collection of data on individual network assets and the estimation of the required level of backup power for different stress conditions. Values for these indicators would not vary for different stress levels, but the amount of backup power capability required would change. Therefore, the values for these indicators must be interpreted in the context of a specific stress scenario.

4.3.6 Survivability

As defined in Section 4.2.6, network survivability relates to the number of surviving network assets at the facility layer. The survivability of certain combinations of these assets determines the survivability of links, connections, and services.

Physical Survivability. Physical survivability is defined as the percentage of network assets (e.g., switches, repeaters, transmission hubs) that "survive" under severe stress conditions. For example, the NCS models the effects of predicted nuclear attack laydowns on telecommunication assets. Assets that have a probability of survival equal to or greater than 0.5 are considered to be "surviving" assets. Physical survivability applies to the facility layer of the network framework.

Evaluation of Physical Survivability. Physical survivability is a relevant indicator of network survivability because a sufficient number of network assets must be functioning to maintain an acceptable level of service under stress conditions. However, it can be misleading if other network robustness indicators are not included in the analysis. For example, a small number of damaged assets in a large network will not significantly reduce the overall physical survivability of the network, but the impact on other indicators, such as call completion probability, may be substantial.

Although physical survivability may not be an accurate indicator of network robustness, many other network robustness indicators require the calculation of physical survivability as an intermediate step. For example, the PSN connectivity matrix used to calculate call completion probability is generated based on physical survivability. Physical survivability data on specific network components can be used to derive the values of physical diversity, connectivity, and accessibility indicators.

Physical survivability is a simple concept, and the NCS is familiar with this indicator. A limitation of this indicator is that it requires threat prediction, either deterministic or probabilistic. In other words, physical survivability must be based on predicted attack scenarios or other threat scenarios. For example, Booz•Allen & Hamilton is helping the NCS develop models for predicting the physical survivability of telecommunication assets after earthquakes or other natural disasters. Physical survivability can be determined for a range of stress conditions, but this requires a significant modeling effort.

Service Survivability. Service survivability is a function of the number of users that have a specific service after stress has occurred. This indicator requires assumptions about when service is surviving or not surviving. For example, the NCS could assume that if the necessary network components survive, then service survives for a set of NS/EP telecommunication users. It is possible for network stress to degrade network service to a point that it becomes unacceptable (i.e., service does not survive). However, for NCS analyses, it is difficult to predict the value of specific performance measures that affect the acceptability of a service (e.g., signal-to-noise ratio, call setup delay). Therefore, service survivability is based on the survivability of physical assets needed to support a service.

One technique for examining service survivability is to use the survivability matrix proposed by Richard Cardwell and Gary Brush (Cardwell and Brush 1990). Cardwell and Brush also propose a technique for graphically displaying the information in the survivability matrix. This technique is called the survivability starplot. The survivability matrix and starplot are helpful in assessing the worst-case damage affecting service capability when the network experiences some specified number of node and/or link failures. The following example of a survivability matrix and starplot is adapted from an article by Cardwell and Brush (Cardwell and Brush 1990).

Figure 16 shows a configuration of a common-channel signaling network. Four types of service are defined based on the signaling network elements required to provide the service. A quadruple [X1,X2,X3,X4] is defined to represent the total number of customer-service combinations that are possible for a specific level of stress (i.e., node and link failures). The survivability matrix, *S*, is defined as the "worst" level of customer-service combinations that are possible if *i* links and *j* nodes fail. For example, the entry for no failed nodes and two failed links assumes that both links to the single copy of database 1 fail. Service 1 requires access to database 1. Therefore, no customers can use service 1, and all other services survive. The survivability matrix and starplot for this example is contained in Figure 17.

Service survivability can be calculated from a weighted sum of the components of the quadruple. For example, [X1,X2,X3,X4] will be considered less survivable than [Y1,Y2,Y3,Y4] if the weighted sum of the Xi is less than the weighted sum of the Yi. The relative importance of specific services is reflected in the weightings.

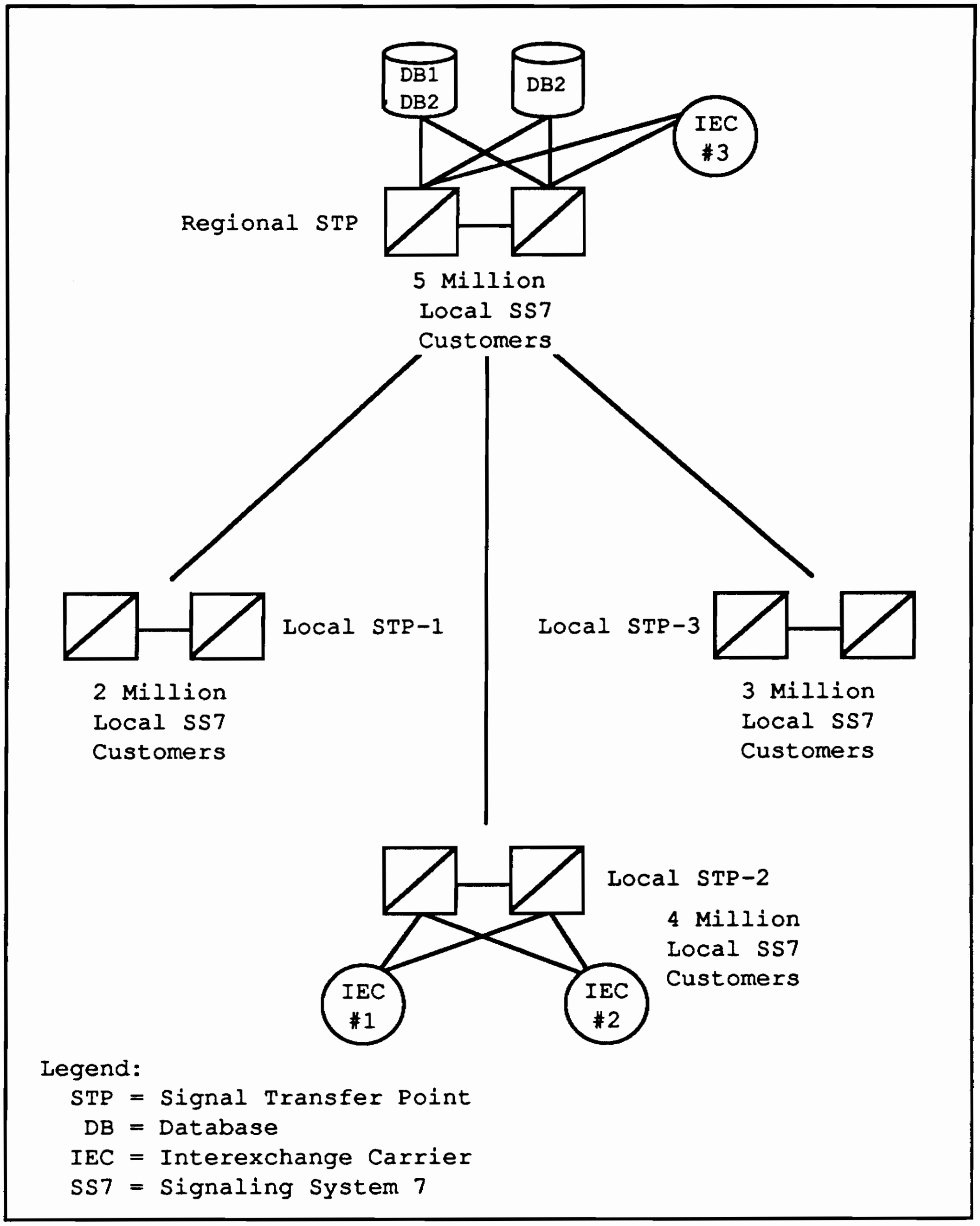


FIGURE 16: Example Common-Channel Signaling Network

Survivability Matrix

LINKS FAILED \ NODES FAILED	0	1	2
0	[14,14,42,14]	[0,14,42,14]	[0,0,8,9]
1	[14,14,42,14]	[0,14,42,14]	[0,0,8,9]
2	[0,14,42,14]	[0,0,42,14]	[0,0,7,8.5]
3	[10,10,18,14]	[0,10,18,14]	[0,0,7,8.5]

Survivability Starplot

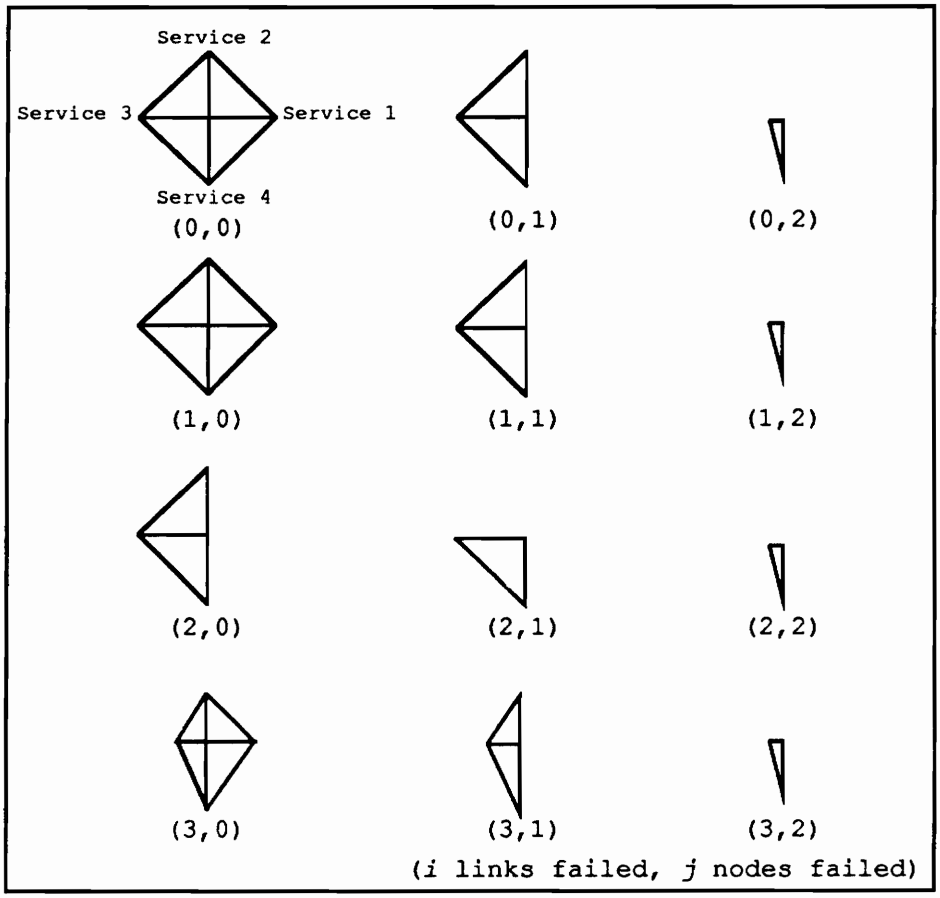


FIGURE 17: Survivability Matrix and Starplot

The survivability starplot shown in Figure 17 is a graphical display of the matrix. Each service is represented by an arm from the center of the plot. The length of each arm is proportional to the ratio of available capability to the maximum capability in the unstressed environment. The survivability matrix and starplot are useful for examining portions of the PSN or small networks. However, this technique would be difficult to apply to a network of hundreds of nodes and links.

Evaluation of Service Survivability. Service survivability is an important indicator for the NCS to consider in its analyses. The overall goal of the NCS is to ensure that all NS/EP telecommunication users have surviving service for any type of stress conditions. The concept of service survivability is simple. However, the methods of calculating its value are complicated. Developing a standard methodology for measuring the service survivability of the PSN with and without enhancements may also be difficult. The use of the survivability matrix and starplot to determine service survivability is computer-intensive for networks the size of the PSN. Other methods for calculating service survivability should be defined, particularly for analyzing more severe stress scenarios.

4.3.7 Discussion of Capability Indicators

Table 5 lists the proposed capability indicators for each robustness characteristic. The indicators vary with respect to their NCS relevance, simplicity, ease of calculation, and sensitivity to specific stress scenarios. Section 5 includes further discussion of these indicators.

Technical literature reviewed for this project contained many other system effectiveness indicators. However, these other indicators are not considered appropriate for the NCS to use in its analyses of network robustness. Some of these indicators are described briefly below. Reasons for not proposing these indicators for NCS consideration are provided.

Network Reliability. As defined in an article by F. T. Boesch, network reliability is "the probability that the network has some path between each pair of nodes" (Boesch 1988). A network is depicted as a graph G with n nodes and e edges. Edge weights represent the probability that the edge is operational. The network is considered operational if a subgraph H, which includes all nodes of G, is connected and has all of its edges operational. The subgraph G is an operating state of the network. Network reliability is the probability that the network is in an operating state.

TABLE 5: List of Capability Indicators

CHARACTERISTIC/INDICATORS	DEFINITIONS
CONNECTIVITY	
- Relative Connectivity	- Ratio of actual node-pairs connected to total node-pairs.
- Mean Network Size	- Average number of switches that any switch in network connects to directly.
- LATA Connectivity	- Number of access/egress paths from EO to IEC POP divided by number of EOs in LATA.
PHYSICAL DIVERSITY*	
- P-Diversity	- Sum of the diversity contributions of all routes in a route set.
RESTORABILITY	
- Mean Time to Repair	- Mean time to repair an individual network component.
- Mean Time to Restore	- Mean time to restore a transmission link, connectivity, or service.
ACCESSIBILITY	
- Call Completion Probability (Blocking Probability)	- Probability of establishing a connection in a circuit-switched network. (Probability that a call will be blocked due to damage or congestion.)
- Throughput	- Number of information bits correctly transferred per unit time.
ENDURABILITY	
- Average Power Reserve Capacity	- Average amount of backup power reserves for network assets expressed in units of time.
- Percentage of Network Assets with Power Reserves	- Percentage of network assets with a specified level of backup power reserves.
SURVIVABILITY	
- Physical Survivability	- Percentage of network assets that survive under severe stress conditions.
- Service Survivability	- Number of users with access to one or more surviving services

*Equivalent Diverse Routes is not listed because it can result in intuitively-incorrect results. P-diversity is a better indicator of physical diversity.

An operating state assumes all nodes are operational and connected. Note that this indicator ignores network routing rules (e.g., number of switches/nodes allowed in tandem). The calculation of network reliability based on this article's definition is not relevant because the NCS is concerned about stress conditions that may result in failed nodes and connectivity loss.

Cost-to-Survivability Ratio. An article on survivable network architectures for broadband networks used a cost-to-survivability ratio to evaluate alternative architectures. The article defines survivability as "the capability for the network to recover from a single failure" (Wu, Kolar, and Cardwell 1988). The article discusses a methodology for designing a network, not analyzing or enhancing an existing network. The cost-to-survivability ratio is the cost in dollars per survivable circuit. It is computed by dividing total network cost by the product of survivability (percent) and total circuits. The survivability term in the calculation is the portion of demand that is still intact when a restoration scheme is enforced. Cost-to-survivability ratio is not applicable to the NCS's problem because the NCS is not designing a new network. In addition, this indicator includes cost considerations, which are separate from network robustness.

Expected Cost of Disturbance. The expected cost of disturbance is an indicator of the economic impact of a traffic disturbance resulting from a failure. This indicator is defined in an article by Peter Dirke (Dirke 1988). It is useful in analyses by telecommunication carriers of investments in network robustness. Telecommunications service providers can estimate the cost of an outage in terms of lost revenues. It is difficult, if not impossible, to estimate the economic impact of losing NS/EP telecommunications during a national emergency. In addition, this project addresses indicators of network robustness. Cost is a separate evaluation criterion, not an element of robustness.

User Lost Erlang. An article by John McDonald discussed the dependability of public networks (McDonald 1992). The article describes a new indicator for quantifying the magnitude of an outage. This indicator is called the User Lost Erlang (ULE), and its formula is shown below:

$ULE = \log(E \times H)$ for ExH greater than 1
where E is the estimated average user traffic in erlangs lost during the outage, and H is the outage in hours.

The ULE may be useful for carriers to use to analyze the magnitude of outages. However, it is not an indicator of the capability of a network to maintain or restore service. The ULE can be used to maintain a record of the magnitudes of past outages. It is not useful in the analysis of NCS-defined network enhancements.

5. CONCLUSIONS AND RECOMMENDATIONS

The world is becoming more dependent on communications. "As we become more dependent on networks, the consequences of network failure become greater and the need to reduce network vulnerabilities increases commensurately" (National Research Council 1989). The NCS is charged with ensuring telecommunications to support the NS/EP needs of the Federal Government under all types of stress conditions. To fulfill its charge, the NCS is identifying and implementing capabilities to enhance the PSN for NS/EP telecommunication users.

Network robustness is a key criterion for analyzing the PSN with and without Government-funded enhancements. Robustness is not the only system effectiveness criteria, but it is the focus of this project. Robustness is defined as the ability of a network to maintain an acceptable level of service during stress conditions or to restore an acceptable level of service soon after network stress has occurred. Network robustness cannot be measured directly, but rather a set of network characteristics and corresponding capability indicators is needed. An article on rating telecommunications system performance provides insight on the process of developing indicators:

> At present, there does not appear to be any well-defined algorithm for developing candidate objective measures. Often, intuition, creativity, and ad hoc procedures must be used to obtain a candidate set of objective measures that is both meaningful and practical to implement (Wolf et al. 1991).

The process used in this project to develop indicators of network robustness starts with a review of the NCS mission and NS/EP telecommunication functional and service requirements. Capability indicators should be traceable to system requirements. An understanding of the systems to be analyzed is also essential to defining indicators that are meaningful. Results of the mission and requirements analysis and the review of systems to be analyzed lead to the definition of robustness and the identification of network characteristics that relate to robustness. These characteristics are connectivity, physical diversity, restorability, accessibility, endurability, and survivability. The network robustness framework is used to aid in the explanation of network characteristics and indicators.

Analyzing network robustness requires multiple indicators to capture all of the aspects of robustness. The use of one or two indicators can be misleading. For example, the connectivity of a network under a specific stress condition is not a sufficient indicator of the network's ability to maintain or restore an acceptable level of service under a range of stress conditions. A network can have a high value of logical connectivity, but have poor physical diversity. In this situation, the loss of a single physical link can result in the loss of multiple logical connections.

The indicators introduced in Section 4.3 and listed in Table 5 are evaluated with respect to relevance, simplicity, modeling complexity, and sensitivity to specific network stress scenarios. Table 6 summarizes the results of the evaluation for each indicator.

The NCS should consider the capability indicators defined in Section 4.3 as candidate indicators. The NCS should not use all of these indicators for all of its analyses. In some cases, information gained from different indicators overlaps, such as values for blocking probability and call completion probability or relative connectivity and mean network size. Capability indicators should be selected based on the following factors:

- Analysis purpose
- Enhancements to be analyzed
- Stress conditions to be considered

TABLE 6: Summary of Evaluation Results

INDICATOR	ADVANTAGES	DISADVANTAGES
Relative Connectivity	- Applies to all types of networks - Can be defined for any set of node-pairs - Relevant indicator for many PSN enhancements - Decision-maker/audience familiarity - Availability of data - Can be analyzed for all types of stress	- Does not indicate effects of congestion - May not be appropriate for less severe scenarios
Mean Network Size	- Applies to all types of networks - Easy to understand - Availability of data - Useful for comparing different networks	- Not appropriate for analyzing end-to-end connectivity - More appropriate for analyzing unstressed networks - Does not indicate effects of congestion - Can be misleading if tandem links are allowed in network
LATA Connectivity	- Applies to LEC networks and connection to IEC networks - Can examine individual LATA or average for all LATAs - Relevant for many CNS and ECC enhancements	- Can be misleading because physical diversity is unknown - Does not indicate effects of congestion
P-Diversity	- Easy to understand - Relevant indicator for NCS enhancements - Gives intuitively-correct results - Applies to stressed and unstressed networks - Applies to all types of networks	- Insufficient data on LEC networks - Computer processing requirements

TABLE 6: Summary of Evaluation Results (Continued)

INDICATOR	ADVANTAGES	DISADVANTAGES
Mean Time to Repair	- Indicator of restorability for facility layer - Easy to understand - Applies to all types of networks	- Not relevant for currently-defined enhancements - May be difficult to obtain data to support indicator
Mean Time to Restore	- Flexibility (applies to links, connectivity, and services) - Relevant to NCS mission - Applies to all types of networks - Captures benefits of initiatives related to deployable assets - Easy to understand	- May be difficult to quantify (requires historical data and assumptions about enhancements) - Must be related to a specific stress scenario
Call Completion Probability (or Blocking Probability)	- Relevant indicator to NCS mission and proposed enhancements - Applies to circuit-switched networks - Decision-maker/audience familiarity - Availability of PSN data and modeling tools - Applies to damaged and congested networks	- Requires assumptions about traffic - Computer processing requirements
Throughput	- Applies to data communications - Applies to unstressed, damaged and congested networks - Easy to understand - Availability of software that computes throughput	- Requires assumptions about traffic - Current NCS efforts focus on voice communications

TABLE 6: Summary of Evaluation Results (Continued)

INDICATOR	ADVANTAGES	DISADVANTAGES
Average Power Reserve Capacity	- Indicator of endurability of a network - Relevant to NCS mission - Applies to all types of networks - Easy to calculate - Easy to understand	- Not relevant for currently-defined enhancements - May be difficult to obtain data to support indicator
Percentage of Network Assets with Power Reserves	- Indicator of endurability of a network - Relevant to NCS mission - Applies to all types of networks - Easy to calculate - Easy to understand	- Not relevant for currently-defined enhancements - May be difficult to obtain data to support indicator
Physical Survivability	- Relevant to NCS mission and enhancements - Required indicator for calculating other indicators - Applies to all types of networks - Easy to understand	- Can be misleading if used as only robustness indicator - Requires threat prediction (deterministic or probabilistic)
Service Survivability	- Relevant to NCS mission and enhancements - Useful for drawdown analysis of networks (worst-case effects of node and link failures) - Useful for analyzing survivability of multiple services - Relatively simple concept	- Calculation methodology may be complicated (particularly for analyzing large networks) - Computer processing requirements

- Background of decision-maker(s)/analysis audience
- Technical/resource limitations.

The purpose of an analysis should be considered before selecting indicators and developing a methodology for calculating values. The purpose of the NLP supporting analysis, which is conducted annually, is to show the NCS member organizations that the NLP will improve network robustness. There is no trade-off analysis of multiple alternatives. The NCS should use a comprehensive set of indicators to illustrate all of the benefits of the NLP. There is no need to aggregate the results into one composite value that can be compared to composite values for other alternatives.

An analysis of proposed ECC features has a different purpose than the NLP supporting analysis. The NCS is planning to perform an analysis of all of the ECC features listed in Table 3 to determine which features are the most cost effective. A possible approach for this analysis is to group the ECC features according to the way the features enhance the network. For example, some features alleviate trunk congestion and other features improve network access diversity from NS/EP user locations. Subsets of capability indicators can be selected for each group of features. The NCS can then determine which feature(s) in each group provide the greatest improvement in network robustness. The NCS can combine the robustness results with other evaluation criteria, such as cost or development risk. Methods for aggregating results for multiple criteria include the use of z-scores or the application of the Analytic Hierarchy Process. Z-scores are used to translate objective and subjective indicators to a common scale. Z-scores are determined by examining where values for a particular indicator fall on a distribution curve in terms of the number of standard deviations above or below the mean. (Conversations with Michael Bolles of the Department of the Navy and Booz•Allen colleagues are the sources of information on z-scores.) The Analytic Hierarchy Process, developed by Thomas Saaty, requires construction of a hierarchy of criteria with alternatives at the lowest level. Pairwise comparisons are made to calculate criteria weights and the degree of preference of one alternative over another (Canada and Sullivan 1989).

The enhancements to be analyzed affect the appropriateness of specific capability indicators. For instance, the NCS could use the service survivability indicator to analyze the benefit of the survivable signaling enhancement in the AT&T network. The network robustness framework, which was presented in Section 4.1.3, is a useful way to depict various network functions and to understand where specific enhancements apply. Each layer builds upon the lower layers to provide robust services to users. The indicators defined in this project are mapped against the four-layer network framework in Figure 18. Table 7 maps NLP enhancements against the layers of the network framework. A similar table could be constructed for the ECC features defined in Table 3. The matrix and table can be used to relate enhancements to indicators. For example, enhancements to the logical layer of the model, such as robust nonhierarchical routing, require the use of connectivity indicators to analyze robustness improvements. The process of selecting indicators for specific enhancements may occur in two steps: relating enhancements to robustness characteristics and relating characteristics to indicators.

Network robustness refers to the capability of a network to function under stress conditions. Stress conditions can include network damage and/or congestion to varying degrees. The type of stress conditions to be considered in an analysis should be considered in the selection of capability indicators. For example, call completion probability provides insight on the effects of network congestion on robustness. This insight cannot be obtained from indicators of connectivity and physical diversity.

NETWORK LAYER ROBUSTNESS INDICATOR	1 Facility	2 System	3 Logical	4 Service
Relative Connectivity			●	
Mean Network Size			●	
LATA Connectivity			●	
P-Diversity	●	●	●	
Mean Time to Repair	●			
Mean Time to Restore		●	●	●
Call Completion Probability (Blocking Probability)				●
Throughput				●
Average Power Reserves	●			
Percentage of Assets with Power Reserves	●			
Physical Survivability	●			
Service Survivability				●

FIGURE 18: Capability Indicators Versus Network Framework Layers

TABLE 7: NLP Enhancements Versus Network Framework Layers

TECHNICAL ENHANCEMENT:		LAYER 1 FACILITY	LAYER 2 SYSTEM	LAYER 3 LOGICAL	LAYER 4 SERVICE
GETS	710 DIALING PLAN			- routing 710 calls to IECs	- 710 access code
	INTERNATIONAL ACCESS				- access to international destinations
	PERSONAL IDENTIFICATION NUMBERS				- access control
	PRIORITY TREATMENT			- trunk subgrouping or reservation	- priority access - priority transport
	ROBUST NON-HIERARCHICAL ROUTING			- dynamic routing	
	SURVIVABLE SIGNALING NETWORK	- equipment reliability enhancements	- link diversity	- adaptive routing	- survivable signaling service
CSI	ORDERWIRE				- service management
	SATELLITE TRUNKS AND GATEWAYS	- physical diversity - hardened tail circuits	- link diversity - excess capacity	- NS/EP-dedicated capacity	
	INTEROPERABLE TT&C	- redundant systems - redundant facilities		- capacity allocation	- network control - service allocation
CNS	CARRIER INTERCONNECT	- physical diversity	- link diversity - excess capacity	- dedicated T1 connections	- access control
	CELLULAR	- physical diversity	- additional capacity from LEC		- cellular service - priority service
	MOBILE/ TRANSPORTABLE TELECOM	- physical diversity - mobile assets	- link restoral capability	- NS/EP-dedicated capacity	- access restriction to restored links
NATIONAL TRANSPORTABLE TELECOM CAPABILITY		- multimedia - mobile assets - physical diversity	- link diversity - excess capacity	- NS/EP-dedicated capacity	- cellular service

The severity of stress on the network can influence the selection of indicators. Indicators such as LATA connectivity and physical diversity are more relevant for less severe stress scenarios. The survivability matrix/starplot technique is also useful for analyzing the effect of a limited number of node and/or link failures on a portion of the PSN. End-to-end relative connectivity and call completion probability are more appropriate for severe stress scenarios. An indicator such as call completion probability will not change significantly if the network experiences one or two node or link failures. Service survivability is a useful indicator for examining the effects of targeted scenarios on the PSN. Targeted network damage refers to threat scenarios where telecommunication network assets are targeted for disruption based on the potential impact on service. These scenarios assume perfect knowledge of the PSN. This type of analysis is also referred to as a drawdown analysis where a robustness indicator (e.g., call completion probability) is plotted against number of targeted assets.

The background and preferences of the decision-maker or analysis audience influence the selection and use of capability indicators. Some decision-makers or audiences are comfortable with complex, quantitative analyses. Other decision-makers or audiences prefer an analysis that rates alternatives as red, yellow, or green for each network characteristic. Most of the indicators described in Section 4.3 can be explained through simple definitions or examples. The complexity of the indicators pertains to the assumptions required and the calculation method. The presentation of results can be tailored to the background and preferences of the decision-maker and/or analysis audience.

Technical and resource constraints should also be considered before selecting capability indicators. The NCS may not have data needed to support one or more of the indicators defined in Section 4.3. For example, currently-available LEC data includes information on logical connectivity, but not on the physical routing of transmission links. P-diversity cannot be calculated for LEC networks without additional data. The availability of data to support indicators is a constraint on their use. Computer processing resources may also be a constraint. Determination of service survivability for multiple services under multiple stress levels requires significant time and processing resources.

The results of this project include a qualitative understanding of network robustness and the network characteristics related to robustness. Project results also include a set of candidate network robustness indicators and considerations for selecting and using these indicators. The

NCS should consider these capability indicators for the NLP supporting analysis, the cost/benefit analysis of proposed ECC features, and other analyses.

A recommended next step is to test the indicators using existing data and modeling tools to better understand their usefulness and limitations. Specifically, procedures for predicting values for these indicators should be developed and implemented on a trial basis. Several enhancements should be analyzed for a limited number of stress scenarios to see what numerical results are obtained. These numerical results could then be checked by subject matter experts for intuitive correctness. Testing the indicators will also provide more insight on the difficulty of modeling these indicators and on the technical and computing resources required. Implementing some or all of the indicators may require additional PSN data collection, development of assumptions, modification of existing modeling tools, and/or acquisition of new modeling tools. The costs of these actions should be estimated and weighed against the benefits provided by the indicators—better understanding of the effects of PSN enhancements on network robustness.

The NCS should begin to incorporate the indicators that are feasible to implement in its future analyses. An effective way to use these indicators is suggested in an article by Rosemary Wild and Joseph Pignatiello, Jr. (Wild and Pignatiello 1991). The authors of this article use Genichi Taguchi's method for improving product and process quality in manufacturing to develop a strategy for using simulation to design robust systems. The purpose of using simulation experiments is to design systems that are robust to changes in variables that cannot be controlled in the real world. By simulating system performance over a range of environmental conditions, the designer can determine what values of controllable variables (i.e., variables that can be controlled in the real world) yield the best average performance and/or the least variability in performance.

The NCS should view the type, number, and placement of network enhancements as the controllable variables and stress conditions as the uncontrollable variables. Values for selected robustness capability indicators could be generated from simulations of the PSN with and without enhancements for a range of stress conditions. The combination of enhancements that yields the best average performance (i.e., best values for capability indicators) and minimizes variability should be implemented to ensure a robust NS/EP telecommunications capability.

6. SUMMARY

The purpose of this systems engineering project is to define capability indicators for analyzing the robustness of telecommunication networks. These indicators could be used by the National Communications System (NCS), a confederation of 23 Federal departments and agencies. The NCS is charged with the development of a national telecommunications capability to support critical communication requirements during times of crisis or emergency.

The NCS is developing and implementing network enhancements to increase the robustness of the public switched networks (PSN). Network robustness is defined as the capability of a network to maintain an acceptable level of service during stress conditions or to restore an acceptable level of service soon after network stress has occurred. The PSN comprises the local and long distance telephone networks, cellular networks, and public packet-switched data networks. Stress conditions cause physical damage and/or traffic congestion in the PSN (e.g., conditions resulting from natural disasters or hostile threats). The capability indicators discussed in this report could be used by the NCS to analyze the improvements in network robustness afforded by Government-defined enhancements.

A review of literature revealed the need to develop a clear definition of network robustness that relates to the NCS mission and national security and emergency preparedness (NS/EP) telecommunication requirements. Network characteristics and corresponding capability indicators are developed based on the definition of network robustness. The methodology used in the project included six steps:

- STEP 1: Review NCS mission and NS/EP telecommunication requirements
- STEP 2: Characterize systems to be analyzed
- STEP 3: Develop understanding of network robustness
- STEP 4: Define capability indicators
- STEP 5: Evaluate capability indicators
- STEP 6: Develop conclusions and recommendations.

An understanding of the NCS mission, NS/EP telecommunication requirements, the PSN, and the existing and planned network enhancements is necessary to define network robustness and capability indicators.

The NCS is responsible for developing a capability that builds on the PSN to support NS/EP telecommunication requirements during all types of crises or emergencies. This capability must support users that are distributed nationwide. It must support current voice and voiceband data requirements, as well as accommodate future requirements for high-speed data and video communications. Policy guidance identifies some of the desired characteristics of the capability, such as connectivity, interoperability, and survivability.

The NCS is taking advantage of the inherent robustness of the PSN, rather than designing and developing a complete, private network. The PSN includes the circuit-switched networks of the local exchange carriers (LEC), interexchange carriers (IEC), and cellular service providers. The PSN also includes the public packet-switched networks supporting data communications. The PSN is currently evolving to an Integrated Services Digital Network (ISDN). The goal of ISDN is to use end-to-end digital connectivity and common-channel signaling to integrate voice and nonvoice services.

One way to describe telecommunication networks is to use the network robustness framework. This framework includes four layers: the facility layer (layer 1), the system layer (layer 2), the logical layer (layer 3), and the service layer

(layer 4). The functions of the lower layers support the functions of the higher layers. Network robustness indicators and Government-defined enhancements can be mapped against the four-layer framework.

The NCS has a National Level NS/EP Telecommunications Program (NLP) comprising several component programs: Government Emergency Telecommunications Service, Commercial Network Survivability, and Commercial SATCOM Interconnectivity. Specific network enhancements are developed and implemented under these component programs. The NCS is also examining the costs and benefits of a number of Enhanced Call Completion (ECC) services. The ECC services were defined recently by a task force of telecommunications industry representatives. Some of these services may be incorporated in the NLP, and others may be provided at the direct request of specific NS/EP telecommunication users. The capability indicators defined in this project could be used to analyze the benefits of the NLP and ECC services.

For this project, network robustness is defined as the capability of a network to maintain an acceptable level of service during stress conditions or to restore an acceptable level of service soon after network stress has occurred. This definition is consistent with some of the definitions of robustness and survivability found in technical literature.

Network robustness cannot be measured directly, but rather it is based on capability indicators for several network characteristics and the judgment of the decision-maker(s). Network characteristics related to robustness are described below:

- **Connectivity.** Connectivity is defined as the existence of logical connections between network nodes based on the topology and routing rules of the network. This characteristic applies to the logical layer of the network framework.

- **Physical Diversity.** Physical diversity is the degree to which physically separate and distinct transmission facilities are used to form a connection between two nodes. This characteristic applies to the facility, system, and logical layer of the network framework.

- **Restorability.** Restorability is the ability of a system to be restored, automatically or through manual intervention, to its normal operating state. This characteristic applies to all layers of the network framework.

- **Accessibility.** Accessibility is defined as the probability that a service or a connection can be obtained within given conditions at the request of a user. This characteristic applies to the service layer of the network framework.

- **Endurability.** Endurability refers to the ability of a telecommunications network to operate without commercial power by using backup power systems. This characteristic applies to the facility layer of the network framework.

- **Survivability.** Survivability is the capability of network assets and services to still be functioning following stress on the network. This characteristic applies to all layers of the network framework. The survivability of physical components at the facility layer leads to survivability of links, connections, and services at the higher layers.

Capability indicators are defined for each of the robustness characteristics. These indicators should be quantifiable. They should also be relevant to NCS analysis requirements, easy to explain to decision-maker(s)/analysis audience, and easy to evaluate using computer modeling and simulation tools. As much as possible, the indicators should be independent of specific stress scenarios (i.e., the indicators can be evaluated for various stress conditions).

Capability indicators for connectivity include relative connectivity, mean network size, and local access and transport area (LATA) connectivity. Relative connectivity can be defined as the ratio of actual node-pairs connected to total number of node-pairs. Network size is the number of switches with which a given switch can connect without using an intermediate or tandem switch. Mean network size is the average network size over all switches in a network. LATA connectivity is the number of access and egress paths from end offices to IEC points of presence divided by the number of end offices for a specific LATA.

Capability indicators for physical diversity include equivalent diverse routes (EDR) and P-diversity. The EDR indicator can yield results that are intuitively wrong. Therefore, P-diversity is the preferred indicator of physical diversity. P-diversity is the sum of the diversity contributions of all routes in a route set. It is calculated for a specific node-pair.

Mean time to repair and mean time to restore are capability indicators for restorability. Mean time to repair applies to individual network components at the facility layer. Mean time to restore can apply to the system, logical, and service layers because it can be defined for links, connections, and services.

Capability indicators for accessibility include call completion probability, blocking probability, and throughput. Call completion probability and blocking probability are complementary. Call completion probability is the likelihood that an NS/EP call can be completed (i.e., the probability that a switched connection can be established), and blocking probability is the likelihood that an NS/EP call cannot be completed. Throughput is a capability indicator for data communications. It is defined as the amount of useful and nonredundant information processed or communicated through a network during a specified period of time.

Average power reserve capacity and percentage of network assets with power reserves are indicators of endurability. Average power reserve capacity is the average amount of time that network facilities can operate without commercial power. It depends on the availability of battery power, generators, and fuel. Percentage of network assets with a specified level of power reserve capacity is another useful indicator of network endurability.

The capability indicators for survivability discussed in this report are physical survivability and service survivability. Physical survivability is the percentage of network assets that survive (i.e., continue to exist) under stress conditions resulting from physical damage to the network. Service survivability is a function of the number of users that have one or more specified services after network stress has occurred.

As the world becomes more dependent on communications, network robustness becomes more important. Network robustness is particularly critical to the NCS. This project defines a set of capability indicators that could be used by the NCS to analyze network robustness. The selection of one or more capability indicators should be based on several factors:

- Analysis purpose
- Enhancements to be analyzed
- Stress conditions to be considered
- Background of decision-maker(s)/analysis audience
- Technical/resource limitations.

A logical follow-on action to this project is to test the capability indicators using existing PSN data and modeling tools. Testing the capability indicators defined in this project should provide additional insight on their strengths and limitations. The NCS should consider using some or all of the capability indicators in simulations of the PSN with and without Government-defined enhancements. The combination of enhancements that yields the best values for the selected capability indicators over a range of stress scenarios should be implemented.

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LIST OF ACRONYMS

ANSI	American National Standards Institute
AT	Access Tandem
CCITT	International Telegraph and Telephone Consultative Committee
CNS	Commercial Network Survivability
CSI	Commercial SATCOM Interconnectivity
ECC	Enhanced Call Completion
EDR	Equivalent Diverse Routes
EO	End Office
GETS	Government Emergency Telecommunications Service
IEC	Interexchange Carrier
ISDN	Integrated Services Digital Network
LATA	Local Access and Transport Area
LEC	Local Exchange Carrier
NCS	National Communications System
NLP	National Level NS/EP Telecommunications Program
NS/EP	National Security and Emergency Preparedness
NSTAC	National Security Telecommunications Advisory Committee
POP	Point of Presence
PSN	Public Switched Network
TT&C	Telemetry, Tracking, and Control
ULE	User Lost Erlang

VITA

Karol S. Eller was born June 25, 1965, in Rochester, New York. She lived in the Rochester area until going to Evanston, Illinois, to study at Northwestern University. Ms. Eller graduated with distinction from Northwestern in 1987 with a Bachelor of Science in Electrical Engineering. She has worked at Booz•Allen & Hamilton, an international technical and management consulting firm, since graduation. She is an Associate in the Government Telecommunications Division of Booz•Allen's Technology Center. Ms. Eller has worked on assignments for the National Communications System, the Defense Information Systems Agency, the Uruguayan National Telecommunications Administration, and a law enforcement agency. Ms. Eller currently resides in Falls Church, VA, with her husband, Kevin, and their two cats, Margaux and Josie.

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