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User-Oriented Performance Evaluation of Data Communication Services: Measurement Design, Conduct, and Results

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PREFACE

This report represents a principal end-product of a multiyear performance measurement program conducted by staff members at the National Telecommunications and Information Administration's Institute for Telecommunication Sciences (ITS). This program had two overall objectives. The first objective was to develop a comprehensive, automated performance measurement system to assess data communication performance in accordance with American National Standards X3.102 and X3.141. The second objective was to demonstrate the application of this system in assessing the performance of connections established over representative public data networks and switched telephone networks.

The program began with a series of performance tests conducted during October - December 1983. The data collected in these tests were used to motivate and guide the development of a computer-based ANS X3.141 performance measurement system, and ultimately to validate its successful implementation. The system is comprised of hardware and software elements that extract and process performance data to produce estimated values of ANS X3.102 parameters, together with a variety of graphical presentations of related statistics. The software components of this system may be applied in a wide range of user-oriented performance measurement situations, and are available to telecommunication service providers and users in Federal agencies and U.S. industry organizations. The present report is devoted primarily to the design, conduct, and results of the performance measurements carried out to accomplish the assessment demonstration objective of the ITS program. A companion publication (in several volumes) describing the measurement system in detail will appear shortly.

Many people contributed to the performance measurement program described in this report. The ITS test engineers were given administrative assistance in establishing remote test facilities in San Diego, CA, by G. Walter Parker of the Naval Ocean Systems Center; in Fort Worth, TX, by Jose Fuentes of the General Services Administration; in Seattle, WA, by Dr. Hugh Milburn of the Pacific Marine Environmental Laboratory; in Washington, DC, by Dana Grubb of the National Bureau of Standards; and in Denver, CO, by Fran Polite of the Bureau of Reclamation. Bob Linfield provided preliminary drafts of several sections of the report. Earl Eyman assisted in the software development. Cathy Edgar skillfully used a computer graphics system to produce many high quality figures for the report. Dwight Melcher, Scott Seebass, Tim Gardner, Dan Byers, Chris Bogart, Darin Schwartz, John Waber and Rob Reichert--all students working part-time--contributed enthusiastically and effectively to many aspects of the project. Mike Eubanks, a private consultant, provided a key breakthrough in the design of the network access software. Ginger Caldwell of the National Center for Atmospheric Research provided statistical analysis of several incomplete Latin squares. Lorna Kent provided valuable bibliographical and editorial assistance in the report preparation. Carole Ax and Kathy Mayeda showed their usual persistence and skill in preparing the final manuscript; they were assisted by Payton Hill. Raymond D. Jennings, William J. Pomper, and Evelyn M. Gray served as report reviewers. To all these contributors, as well as to others not mentioned, the authors express their sincere thanks.

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USER-ORIENTED PERFORMANCE EVALUATION OF DATA COMMUNICATION SERVICES: MEASUREMENT DESIGN, CONDUCT, AND RESULTS

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This report presents results of a multiyear data communication performance measurement program conducted at the Institute for Telecommunication Sciences, the research and engineering arm of the National Telecommunications and Information Administration. This program had two specific objectives. The first objective was to develop a comprehensive, automated performance measurement system capable of assessing data communication performance in accordance with American National Standards X3.102 and X3.141. The second objective was to demonstrate a successful application of this new system in assessing the performance of connections established over representative public data networks and switched telephone networks.

This report describes the performance measurements conducted in accomplishing the assessment demonstration objective of the program. The measurements were carried out using a computer-based system that collects and processes performance data to produce estimated values of ANS X3.102 parameters, together with a variety of graphical displays of measurement results. The report includes descriptions of the design and conduct of the measurements and an extensive presentation of performance values.

Key words: American National Standards; data communications; confidence limits; end users; performance measurement; switched networks

1. INTRODUCTION

Deregulation, competition, and rapid growth in the computer communications industry have created a need for uniform methods of specifying and measuring the performance of data communication services as seen by end users. For several years, standards groups in industry and the Federal Government have been working together to meet that need through the development of user-oriented, system-independent performance parameters and measurement methods. The principal results of these efforts are contained in two related American National Standards.

The first, American National Standard (ANS) X3.102 (ANSI, 1983), defines a set of 21 parameters that quantitatively describe the performance of data communication systems and services from the point of view of the end user. The parameters focus on the performance provided to pairs of individual users, but

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they may, with suitable specification of conditions, characterize the overall performance of systems serving many users. The parameters are applicable to all classes of data communication systems, regardless of topology, protocol, architecture, or other design features. This standard was developed by Task Group X3S3.5 of the Accredited Standards Committee on Information Processing Systems and was approved as an American National Standard by the American National Standards Institute (ANSI) in February 1983. ANS X3.102 evolved from an earlier standard, Interim Federal Standard 1033 (GSA, 1979), which was similar in approach and content. The latter standard was developed under the National Communications System's Federal Telecommunications Standards Program (Bodson, 1978). In July 1985, ANS X3.102 was formally adopted as a mandatory Federal Communication Standard (Federal Standard 1033).

The second standard, American National Standard X3.141 (ANSI, 1987), specifies uniform methods of measuring the performance parameters defined in ANS X3.102. The specified measurement methods are general and implementation independent, and may be used to obtain parameter values at any pair of digital interfaces connecting a data communication system to its users. The measurement standard was also developed by Task Group X3S3.5, and was approved as an American National Standard in October 1986. It was based on proposed Federal Standard 1043 (Seitz et al., 1981a, 1981b), which was developed by the National Telecommunications and Information Administration's Institute for Telecommunication Sciences (ITS) as the companion measurement standard to Interim Federal Standard 1033. It is expected that ANS X3.141 will ultimately also be adopted as a Federal Standard.

Together, ANS X3.102 and ANS X3.141 will promote innovation and competition in the data communications industry by providing users with a practical means of specifying and measuring delivered performance. This capability will enable users to make more informed choices among service and equipment alternatives, and will lead, in many cases, to more realistic communication requirements.

1.1 Purpose and Scope of Report

As the measurement standard evolved, it became evident that its impact on the data communications industry could be substantial. Accordingly, it was decided that the standard should be very carefully tested in realistic trial measurements prior to its promulgation and general use. An initial measurement program was conducted by ITS in cooperation with the National Bureau of Standards' Institute for Computer Sciences and Technology (ICST) in 1981-1982. It was based on proposed Federal Standard 1043 and used the Defense Communication Agency's ARPANET as a test bed. In this experiment, a prototype performance measurement system was developed in accordance with the proposed Federal Standard. This system was then used to assess the data communication service provided to a pair of application programs installed in two ARPANET host computers: one located at ITS in Boulder, CO, and the other at ICST in Gaithersburg, MD. Results obtained in the experiment were described in an NTIA report (Wortendyke et al., 1982) and briefly summarized in a subsequent journal publication (Seitz et al., 1983).

The ARPANET experience suggested that substantial improvements in measurement cost effectiveness could be achieved through more complete automation of the measurement process. Proposed Federal Standard 1043 was revised significantly as it evolved into ANS X3.141, in part to facilitate such automation, and it seemed worthwhile to implement these changes in an enhanced measurement system. In late 1983, ITS initiated a second, much more extensive performance measurement program designed to realize and demonstrate these improvements. This program had two specific objectives. The first objective was to develop a comprehensive, automated performance measurement system capable of assessing data communication performance in accordance with ANS X3.102 and ANS X3.141. The second objective was to demonstrate a successful application of this new system in assessing the performance of connections established over representative public data networks and switched telephone networks. Performance data collected by ITS early in the program provided the basis for both the subsequent development and validation of measurement technology and the determination of performance values.

Some selected preliminary measurement results were presented in a short earlier paper (Seitz et al., 1985). The purpose of this report is to provide a detailed and comprehensive account of the ITS performance measurements. The report describes the test plan, whose development led to the formulation of general procedures for designing performance measurement experiments and the inclusion of these procedures in ANS X3.141, and the conduct of the measurements. The report contains an extensive collection of measurement results that describes the observed performance and illustrates the capability of the measurement technology. A companion publication (in several volumes) will present a detailed description of the measurement technology developed during the program: a set of hardware and software elements that extract and process performance data to produce estimated values for the ANS X3.102 performance parameters, together with a variety of graphical displays of measurement results. An interim measurement system, which was used to obtain the results presented in the present report, will be documented in a forthcoming Technical Memorandum.

It is hoped that this report will have two primary impacts. First, by illustrating a successful application of ANS X3.102 and ANS X3.141 in end-to-end data communication performance assessment, it should encourage and facilitate future implementations of these standards. The software developed can be applied in a wide range of user-oriented performance measurements and is available to telecommunication providers and users in Federal agencies and U.S. industry. Several organizations are currently using it. Second, by presenting some representative end-to-end performance data, it should provide a useful baseline for the future development and assessment of data communication services. Ultimately, these results should enhance both the development of data communication services in a competitive environment and the matching of offered systems and services with user needs.

1.2 Report Organization

This report is divided into six principal sections. Section 2 presents an overview of the measurement program and briefly summarizes the software that was developed. Section 3 describes the design of the measurements over three public data networks and two switched telephone networks. Section 4 describes the conduct of the measurements and Section 5 presents detailed measurement results. Section 6 provides a brief summary of program accomplishments.

A series of appendices provides background information and measurement details that may be helpful or of interest to some readers. Appendix A summarizes American National Standard X3.102, which defines user-oriented performance parameters; Appendix B summarizes American National Standard X3.141, which specifies methods of measuring the parameters. Appendix C briefly describes the switched networks utilized in the ITS measurements. Appendix D describes a particular state model of the data communication process that underlies the representation of reference events. Appendix E describes bench calibrations used to validate the test equipment, and Appendix F summarizes proposed and actual test sequences. Appendix G contains a list of ANS X3.102 parameter estimates for each test. Appendix H presents statistical methods used to analyze reduced performance data.

2. PROGRAM OVERVIEW

As noted in Section 1, the potential impact of ANS X3.141 dictated that it should be carefully tested in realistic trial measurements prior to its promulgation and general use. An initial measurement program based on its predecessor, Proposed Federal Standard 1043, suggested that substantial improvements in the cost effectiveness of data communication performance measurements could be realized through more complete automation of the measurement process. The 1043 standard was revised significantly as it evolved into ANS X3.141, in part to facilitate such automation, and it seemed worthwhile to implement these changes in an enhanced measurement system. In 1983, ITS initiated a second, more extensive performance measurement program designed to realize and demonstrate these improvements. This section defines the objectives and describes the various phases of that multiyear program.

2.1 Program Objectives

The first objective of the ITS performance measurement program was to develop a comprehensive, automated performance measurement system capable of assessing data communication performance in accordance with American National Standards X3.102 and X3.141. To achieve this objective, it was necessary to enhance the prototype performance measurement system used in the ARPANET measurements in two respects: first, by adding new experiment design and data analysis software, and second, by revising several of the parameter estimation routines. New design and analysis software was written to assist test engineers in the rather complex mathematical processes of sample size determination and calculation of parameter confidence limits. Statistical criteria for hypothesis testing and factor evaluation were also developed. New estimation routines implemented changes in detailed parameter definitions that had been suggested by the ARPANET measurements and adopted in the approved version of American National Standard X3.102.

The second objective of the ITS performance measurement program was to demonstrate a successful application of this new system in assessing the performance of connections established over some representative public data networks (PDNs) and switched telephone networks. At the time these tests were conducted, the selected PDNs (Telenet, Tymnet, and Uninet) were the largest U.S. providers of packet-switched services, and the selected telephone networks--the public switched telephone network (PSTN) and the Federal Telecommunications System (FTS) were by far the largest U.S. carriers of voiceband data traffic. It was assumed that if the new measurement system could efficiently assess the performance of connections established over each of these networks, it could be used in evaluating a large proportion of the end-to-end data communication services then available. While the planned measurements were certainly not exhaustive, it was anticipated that the values obtained would substantially augment existing data communication performance information and provide a useful baseline for the future development and assessment of data communication services.

Although they examined connections established over three competing PDNs, the measurements conducted by ITS were not designed to be used in network performance comparison. The tested connections included access links exterior to the PDNs, and the performance of such links can substantially affect end-to-end performance. The measurements did not, in general, seek to distinguish performance effects attributable to the access links from performance effects attributable to the PDNs. To be valid, a comparison of PDN performance would require a larger selection of user pairs than those included in the ITS measurements, and the results could be misleading without information on other significant service features (such as cost). To discourage inappropriate comparisons based on the measurements described in this report, each of the public data networks used in the tests is identified by a pseudonym--PDN A, PDN B, or PDN C.

2.2 Program Synopsis

The ITS performance measurement program is shown in Figure 1 to consist of six principal phases or projects. The first four of these correspond to the primary phases of the measurement process defined in ANS X3.141. The diagram identifies significant results of the various phases and indicates their relation to the two overall program objectives defined in Section 2.1--the development of measurement technology and application of this technology in determining performance values. This section briefly describes each phase of the measurement program.

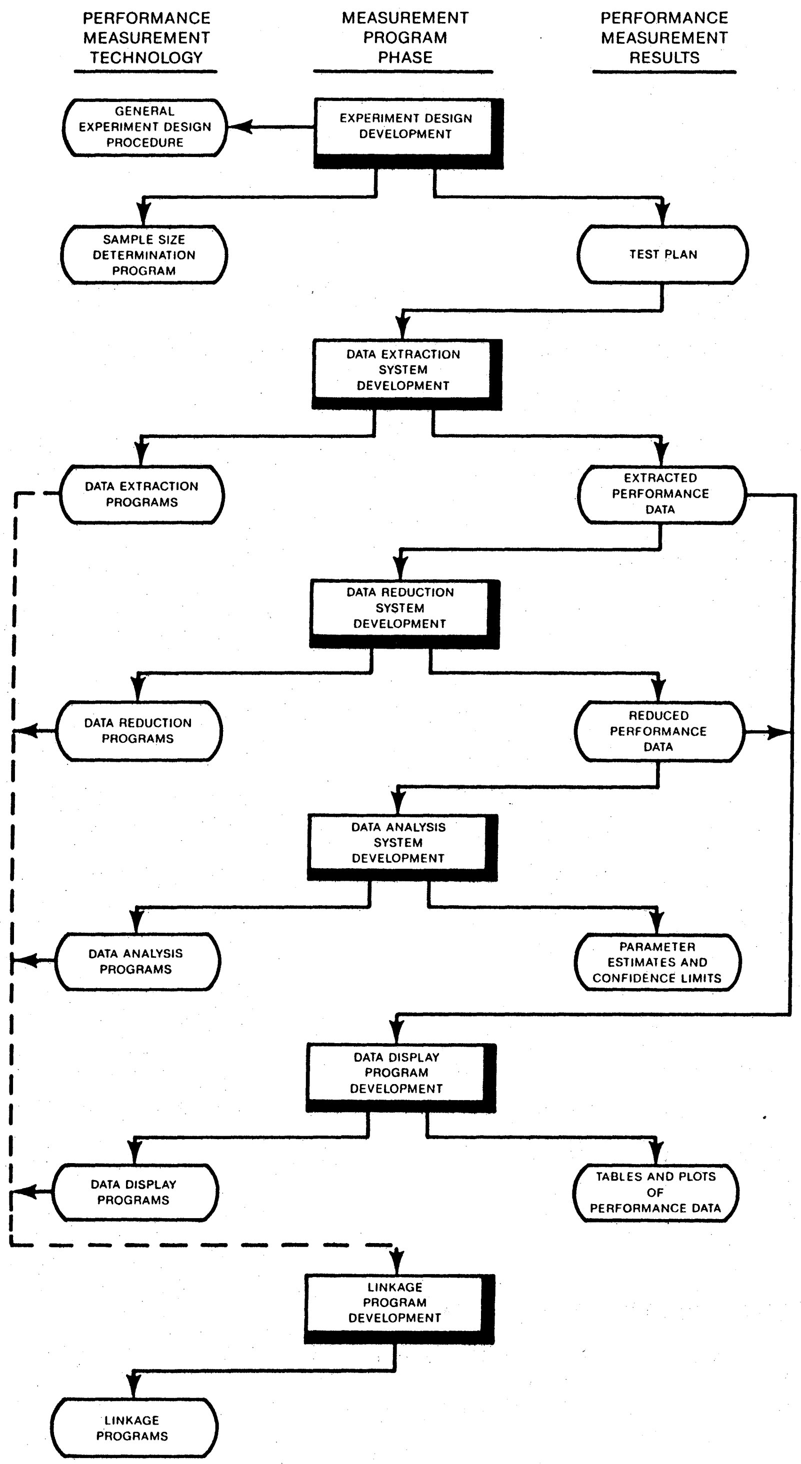

Figure 1. Outline of ITS performance measurement program.

2.2.1 Experiment Design Development

The first phase of the measurement program was the development of a design for a series of data extraction tests. The performance data collected in these tests were intended to provide a basis for

- o the subsequent development and validation of reduction and analysis procedures and
- o the determination of performance values in accordance with the assessment demonstration objective of the measurement program.

This phase of the measurement program produced three significant results. First, the development of the test design led to the formulation of general and systematic procedures for designing data communication performance measurement experiments, and the inclusion of these procedures in ANS X3.141. A summary of the ANS X3.141 experiment design procedures is presented in Appendix B of this report.

Another significant result was a detailed plan for data extraction tests. This plan was the first comprehensive implementation of the experiment design guidelines specified in ANS X3.141 and included elements of each of the three classes of performance measurement experiments defined in the standard: performance characterization, hypothesis test, and analysis of factor effects. Information specified in the test plan included a set of performance factors, the levels of each factor, and the factor level combinations to be used in individual tests. Details of the ITS test plan are presented in Section 3.

The third significant result of the experiment design phase of the measurement program was the development of an interactive FORTRAN computer program that calculates the minimum sample size needed to attain a specified precision in estimating delay, rate, and failure probability parameters. An early version of the program is described in a report by Miles (1984).

2.2.2 Data Extraction System Development

In the second phase of the measurement program, a computer-based system to extract performance data in accordance with ANS X3.141 was developed and used to conduct the tests outlined in the preceding section.

The test scheme is illustrated in Figure 2. Two microcomputer-based test sets were developed: one emulated a network-accessible host computer and resident application program, and the other emulated a remote data terminal and

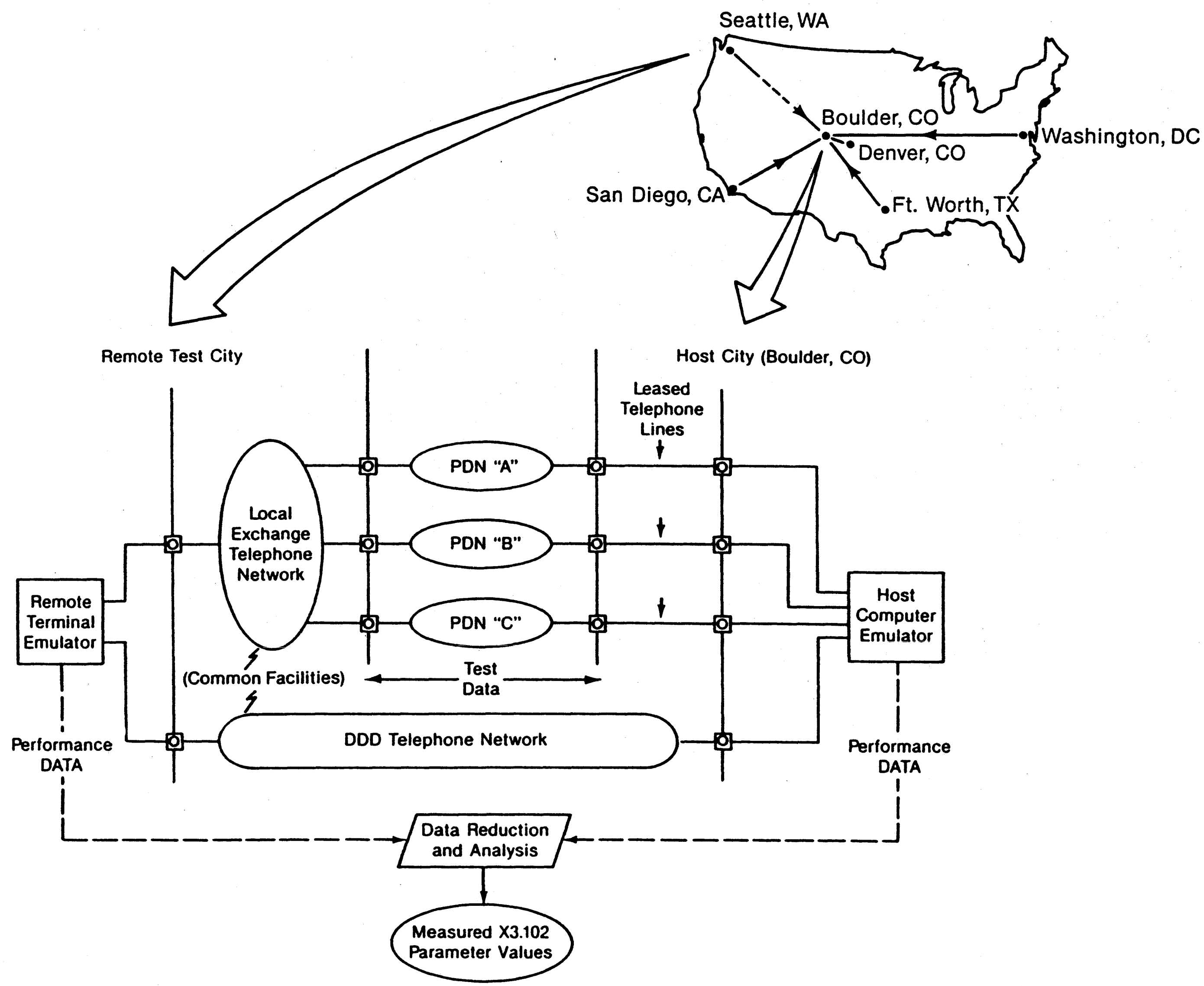

Figure 2. ITS test scheme.

its operator. The host test set was located at ITS in Boulder, CO, and was connected to the Denver offices of each of three PDNs via leased telephone lines. The remote terminal test set was successively placed in five cities (San Diego, CA; Fort Worth, TX; Seattle, WA; Washington, DC; and Denver, CO), where it obtained access to the PDNs via the local exchange telephone network. The remote test set was also able to communicate with the host test set via either the public switched telephone network or the Federal Telecommunications System, bypassing the PDNs.

Each test set included a special measurement application program that performed all local user and interface monitor activities. During testing, the remote test set established connection with the host computer over a selected network, logged into the host and started its measurement application program, transmitted a prepared file of user information, then logged out and disconnected. Collectively, the remote terminal and host measurement application programs recorded all interface events required to estimate a specified set of ANS X3.102 performance parameters in accordance with ANS X3.141. The performance data extracted during each test were transferred via separate error-controlled lines to another computer in Boulder for subsequent reduction and analysis.

The data extraction system includes two distinct subsystems. The first is comprised of the test sets described above, a collection of hardware and software elements that carry out <u>on-line data extraction</u>. During a data extraction test, this subsystem establishes and terminates connections, transmits and receives user information, and records performance-significant interface events. The second data extraction subsystem is a set of computer programs that carry out <u>data conversion</u> procedures. These procedures prepare extracted performance data for input to the subsequent reduction process and are executed off-line after all data for a test have been collected.

The on-line data extraction programs differ somewhat from those used in the earlier ARPANET experiment. The only substantial difference occurs in access and disengagement procedures. The new software emulates the actions of a terminal operator utilizing a switched network to establish and terminate a data communication session with an application program in a distant host. By specifying the relevant sequence of operator commands and system responses in an ASCII-text file, the on-line data extraction programs can be readily adapted to a wide variety of data communication systems.

The data extraction programs are written in the C language to execute under the UNIX™[1] operating system and can be installed and run on many different commercially available computers, including those that might be used in portable test equipment. They can also be adapted to execute under other operating systems that have similar system calls. This flexibility should make the ITS-developed data extraction programs widely useful in future performance measurement applications.

2.2.3 Data Reduction System Development

The third phase of the measurement program was the development of a software system to reduce extracted performance data in accordance with the guidelines specified in ANS X3.141. The resulting system is a set of FORTRAN computer programs and associated I/O files whose primary purpose is to examine extracted performance data to identify individual performance trials and determine their outcomes.

The overall design of the new reduction system is similar to that of the system developed for the ARPANET measurements, but it includes numerous modifications and enhancements. Several significant modifications were required so that performance values were estimated in accordance with the parameter definitions specified in ANS X3.102, rather than those specified in interim Federal Standard 1033. One such modification is the addition of procedures to measure service availability.

A significant enhancement is the production of files that record the outcomes of successive access, block transfer, and disengagement trials identified by the reduction routines. Data recorded for a successful trial include overall and user performance times, whereas data recorded for an unsuccessful trial indicate the particular failure outcome. These outcome records then serve as input to the data analysis phase of a performance measurement. A related enhancement is the recording of pairs of successive failures, which facilitates the consideration of dependence between trials in calculating confidence limits associated with parameter estimates.

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[1]UNIX™ is a registered trademark of Bell Laboratories. Certain commercial equipment, instruments, services, protocols, and material are identified in this report to adequately specify engineering issues. In no case does such identification imply recommendation or endorsement by the National Telecommunications and Information Administration, or that they are the best available for the purpose.

Another data reduction enhancement is the development of procedures to account for the important case in which events at one monitored interface affect subsequent events at the other monitored interface. The inclusion of such remote interface effects facilitates an accurate evaluation of the user influence on performance in a wide range of measurement situations.

The validity of the new reduction system was demonstrated by its successful use in processing the performance data recorded during the tests conducted at the start of the measurement program.

2.2.4 Data Analysis System Development

In the data analysis phase of the performance measurement program, the principal accomplishment was the development and validation of a computer program that calculates performance parameter estimates and their confidence limits, either for a single test or for a selected set of tests that represent the levels of a particular factor. The parameter estimation procedures and the sample size determination procedures outlined in Section 2.2.1 are combined in a comprehensive statistical design and analysis computer program. This program can also be used to determine if the results of a given test satisfy a specified precision requirement. The program is written in ANSI (1977) standard FORTRAN to enhance its portability. It is designed for interactive use.

The analysis routine accounts for possible sequential dependence by treating the successive trials in a test as a first-order Markov process. The usual effect of such dependence is to increase the length of confidence intervals beyond those calculated on the basis of independence. For multiple tests, parameter estimates and their confidence limits are based on a linear model for the analysis of variance in which it is assumed that there are three additive components of variation: among factor levels (e.g., city pairs), among tests within a factor level, and among trials within a test. The program calculates parameter estimates and their confidence limits using three data pooling procedures: pooling all trials from the specified tests, pooling all test means, and using only factor level means. Statistical tests are used to determine the most appropriate pooling procedure.

A related accomplishment was the development of a set of UNIX™ shell scripts to facilitate the use of the program described above to analyze the results of either single or multiple tests. These shell scripts prepare reduced performance data for input to the program, call the program to carry out the analysis, and produce a concise summary of results.

The statistical model and the analysis of multiple tests, along with numerical examples, are presented in Appendix H. The validity of the data analysis software was tested successfully by its use in producing the performance values reported in Section 5.

2.2.5 Data Display Software Development

The data display software consists of a set of auxiliary C language processing and graphical display programs that were developed to facilitate the reduction and analysis of delay data. These programs enable test operators to translate key binary data files into formatted text files and to rapidly generate tables and report-quality graphs that summarize results of individual tests and collections of tests. Tables produced by the data display software include listings of selected components of access and source disengagement times; graphs include box plots, histograms, chronological plots, and regression plots. Such tables and graphs are very helpful in identifying factor effects and performance trends. The data display programs enable an operator to examine key test results while an experiment is still in progress and, if necessary, to make needed changes in test plans and procedures. This can improve measurement efficiency and enhance the value of the results. Many of the figures in Section 5 were produced by these programs.

2.2.6 Linkage Software Development

A set of linkage software modules was developed that enables the data conversion procedures, the data reduction procedures, and certain data analysis procedures for a specified test to be carried out by issuing one command with the test number as an argument. The software consists of a master shell script and a hierarchy of subordinate shell scripts that call all software modules involved in the processing, as well as several UNIX™ utilities. The latter, along with several special C programs, are used to extract and reformat data output by one processing program to serve as input to a subsequent program.

The linkage programs greatly facilitate the processing of test data by eliminating the need for operator involvement in the editing and transfer of data files between the conversion, reduction, and analysis programs. The automation of file editing and transfer also prevents the occurrence of errors in these procedures.

3. MEASUREMENT DESIGN

Constructing a test plan for the 1983 performance measurements led to the development of general and systematic procedures for designing data communication performance measurement experiments and the inclusion of these procedures in ANS X3.141. The test plan provided the first comprehensive implementation of the ANS X3.141 experiment design guidelines and included elements of each of the three major classes of performance measurement experiments defined in the standard: performance characterization, hypothesis tests, and analysis of factor effects. This section uses the ANS X3.141 design specifications as a framework to describe the ITS performance measurement test plan. It consists of five subsections that respectively discuss measured parameters, interface event characteristics, performance factors, measurement samples, and test conditions.

3.1 Measured Parameters

With the exception of Misdelivered Bit Probability and Misdelivered Block Probability, the test plan was designed to obtain data for the measurement of all performance parameters defined in ANS X3.102. Evaluation of the two misdelivery parameters is regarded as optional by ANS X3.102. The performance parameters were divided into two groups to be evaluated in separate types of tests. Access and disengagement parameters comprised one group, and user information transfer parameters comprised the other.

3.2 Interface Event Characteristics

In the tests conducted by ITS, a measurement application program (XMIT)[2] installed in the remote terminal microcomputer

- o performed all activities associated with the originating/source user during each session and

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[2]To assist the reader in identifying program and file names appearing in the body of the text, such names are written with upper case characters regardless of the form used in the actual software.

- o carried out the related interface monitor function by recording all performance-significant events that occurred at the local user/system interface.

A second measurement application program (RECV) performed the corresponding functions in the destination host microcomputer.

The end users in these tests were the XMIT and RECV programs. The user/system interface in each computer was the functional interface between the local measurement application program (XMIT or RECV) and the computer's operating system. At each interface, performance-significant events were associated with particular transfers of control between the local application program and the operating system. Such events included the issuance of WRITE and READ system calls that passed data to or from the network communication port (these events corresponded to transferring control from the issuing program to the operating system), and the associated WRITE COMPLETE and READ COMPLETE responses (these events corresponded to returning control to the issuing program). A typical sequence of significant interface events that occurred during a successful session in an access-disengagement test on a PDN connection is illustrated in Figure 3. The following paragraphs describe these events for each of the three primary data communication functions.

3.2.1 Access Interface Events

Access activities at the XMIT (originating user) interface consisted of

- o the input of a sequence of commands that emulated actions of a terminal operator utilizing a PDN to establish a data communication session with an application program in a distant host and

- o the output of a corresponding sequence of responses that would ordinarily be displayed on the terminal screen.

Each command requested the performance of a particular system function (e.g., dialing the local telephone number of a PDN). The input of a command was accomplished by a single WRITE that passed the command characters from XMIT to the local operating system for transmission from the network port. The normal response to a command (e.g., a CONNECT message) indicated the successful completion of the function, whereas an exceptional response (e.g., a NO CARRIER message) or no response indicated a failure.

The output of a response received from the network was accomplished by a sequence of READs, where each READ passed a single character from the local

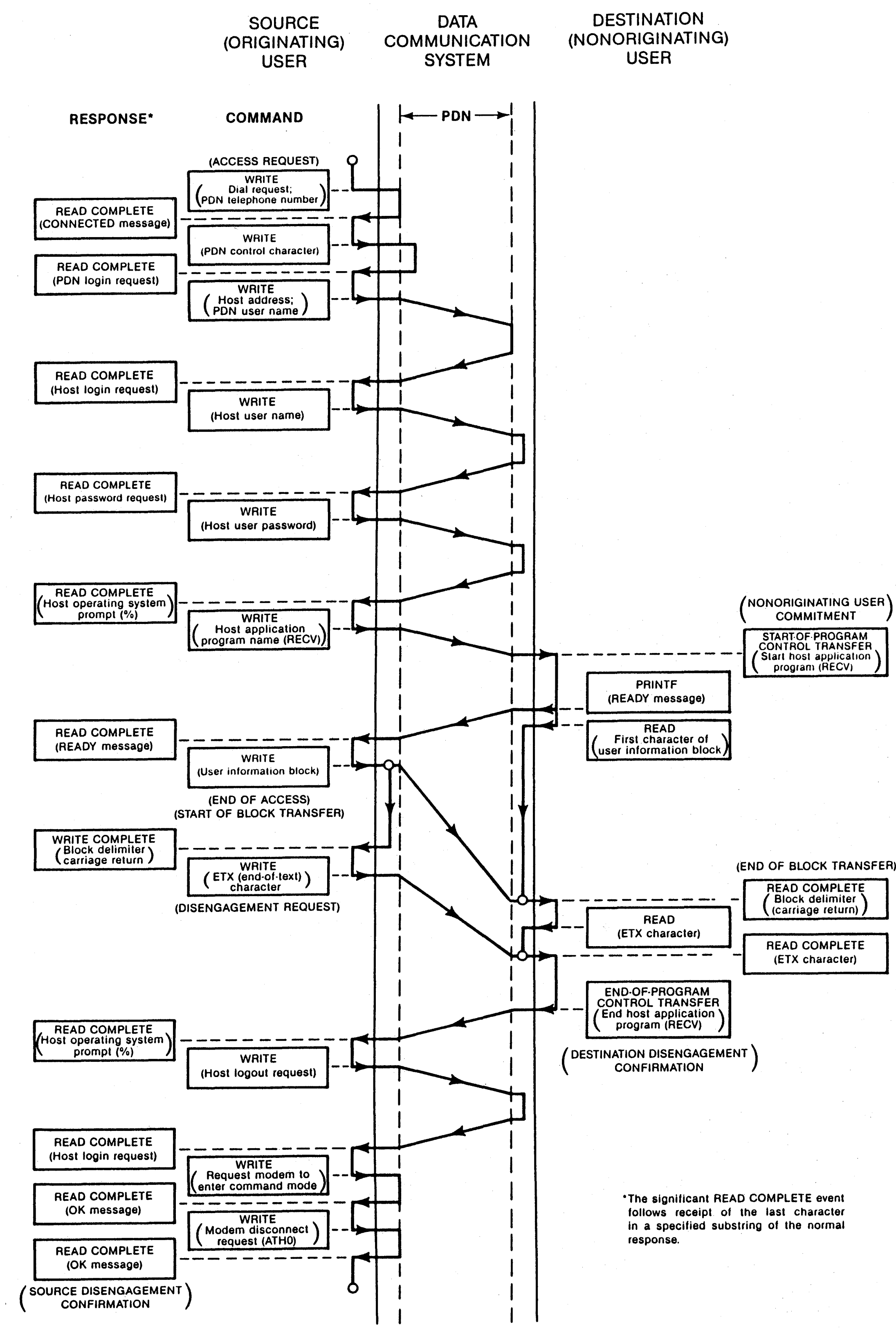


Figure 3. Typical event sequence diagram.

operating system to XMIT. This process continued until XMIT had received the last character in a prescribed substring of the normal response, or until the procedure "timed out" after a specified delay. If the normal response was received, XMIT issued the next command in the sequence; in case of timeout, the session was terminated.

As shown in Figure 3, two significant interface events were associated with each command/response pair. These were the issuance of the WRITE that passed the command to the operating system and the READ COMPLETE event that followed delivery of the last prescribed response character. The issuance of the first WRITE in the illustrated sequence (which entered the command to dial the number of the PDN) was both an Access Request event and an ancillary event that made the system responsible at the local interface for delivering the associated response. The issuance of the last WRITE in the access sequence (which entered the command to start the RECV program) was an ancillary event that had two performance effects. At the local interface, it relieved both entities of responsibility until RECV issued a READY response (described below). At the remote (RECV) interface, it committed the system to participate in the session and made it responsible for starting (i.e., for transferring control to) the RECV program. The issuance of each intermediate WRITE in the access sequence was an ancillary event that made the system responsible at the local interface for delivering the associated response. Each indicated READ COMPLETE event in the sequence was an ancillary event that made XMIT responsible for issuing the next WRITE.

Access activities at the RECV (nonoriginating user) interface consisted of preparatory user procedures (e.g., opening files and initializing pointers), followed by the input of a READY response for delivery to XMIT. The input of READY was accomplished by a PRINTF call (equivalent to a WRITE) issued by RECV.

Two significant interface events were associated with these activities. The first was transfer of control from the host operating system to RECV when execution of that program began. This committed RECV to participate in the session (i.e., it was a Nonoriginating User Commitment event) and was an ancillary event that made RECV responsible for issuing the READY response. The second significant interface event was the issuance of PRINTF. At the remote (XMIT) interface, it made the system responsible for delivering the response. At the local interface it left RECV responsible for issuing a READ to receive transferred user information as described below.

3.2.2 User Information Transfer Interface Events

At the XMIT (source user) interface, user information transfer activities began after delivery of the READY response and consisted of the input of one or more user information blocks. The input of each block was accomplished by two successive WRITE commands issued by XMIT. The first passed the contents of the block (a specified character string) to the local operating system for transmission from the network port, and the second similarly passed a block end delimiter (a carriage return).

As indicated in Figure 3, two significant interface events were associated with the input of each block. These were:

- o the issuance of the first WRITE (which passed the block contents to the system) and
- o the WRITE COMPLETE event that followed the input of the block end delimiter.

The issuance of the initial WRITE was both a Start of Block Input and a Start of Block Transfer event. It was also an ancillary event that had two performance effects. At the local interface, it made the system responsible for completing input of the block (including the end delimiter) and returning control to XMIT. At the remote interface, it made the system responsible for delivering the block to the destination user. The final WRITE COMPLETE event for a block (which may be regarded as an "end of block input" event) was an ancillary event that made XMIT responsible for issuing a WRITE to input the next block or issuing a disengagement request.

User information transfer activities at the RECV (destination user) interface consisted of the output of one or more blocks received from the network. The output of each block was accomplished by a sequence of READ commands issued by RECV. Each READ passed a single received character from the host operating system to RECV, and the process continued (for a given block) until a block end delimiter was delivered.

Two significant interface events were associated with the output of each block. These were:

- o the issuance of the READ that preceded delivery of the first character in the block and
- o the READ COMPLETE event that followed delivery of the end delimiter.

The initial READ for a block was an ancillary event that had one of the following effects:

- o if the associated Start of Block Transfer event had occurred, it made the system responsible at the local interface for delivering the block (including the end delimiter), or

- o if the associated Start of Block Transfer event had not occurred, it relieved both destination entities of responsibility until that event did occur.

The READ COMPLETE event that followed delivery of an end delimiter was both an End of Block Transfer Event and an ancillary event that gave RECV responsibility for issuing the initial READ for delivery of the next block.

3.2.3 Disengagement Interface Events

Disengagement activities at the XMIT interface, like those for access, consisted of the input of a sequence of commands and the output of a corresponding sequence of responses. Here, the command sequence emulated the actions of a terminal operator ending participation in an established data communication session (via a PDN) with an application program in a distant host. The sequence began with an instruction to transfer an end-of-text (ETX) character to the host application program and ended with a request for the local modem to "hang up" the telephone. The input of a disengagement command and the output of the associated response were accomplished by the issuance of a WRITE command and a series of READ commands, respectively, in the same way that access commands and responses were input and output.

Two significant interface events were associated with each disengagement command/response pair. These were:

- o the issuance of the WRITE that passed command characters to the operating system and

- o the READ COMPLETE event that followed delivery of the last prescribed response character.

The issuance of the first WRITE in the sequence (which entered the ETX character) was a Disengagement Request event and was the start of disengagement for both users. It was also an ancillary event that had two performance effects. At the local interface, it relieved both entities of responsibility until the execution of RECV had ended. At the remote interface, it made the system responsible for delivering the ETX character to RECV. The issuance of each subsequent WRITE in the sequence was an ancillary event that made the system responsible at the local interface for delivery of the associated response. Except for the last, each indicated READ COMPLETE event in the disengagement sequence was an ancillary event that made XMIT responsible for issuing the next WRITE. The last READ COMPLETE was the Disengagement Confirmation event for XMIT and terminated the data communication session.

Disengagement activities at the RECV interface consisted of the output of the ETX character transmitted by XMIT, followed by concluding user/monitor procedures (e.g., writing files). The output of the ETX character was accomplished by a READ issued by RECV. Two significant interface events were associated with these activities. The first was the READ COMPLETE event that followed delivery of the ETX character. This was an ancillary event that made RECV responsible for ending after carrying out its concluding procedures. The second significant interface event was returning control to the host operating system after execution of RECV had ended. This was the Disengagement Confirmation event for RECV.

3.3 Performance Factors

The tests were designed according to guidelines similar to those presented in ANS X3.141 for the analysis of factor effects. Performance factors and the levels specified for each factor are summarized in Table 1.

The number of remote terminal sites was limited by time and cost. The selection of particular cities, intended to achieve a wide geographical distribution of locations, was restricted by availability of suitable Federal facilities to serve as test sites.

According to the test plan, each visit to a remote terminal site would encompass five successive days, Monday through Friday. However, Monday morning was reserved for assembling the test equipment, and Friday afternoon was reserved for disassembling it. Collectively, Monday afternoon and Friday morning would then be regarded as a single day of testing. The selection of days and time periods was intended to reveal the effects of time-dependent variations in traffic.

3.4 Measurement Samples

As indicated earlier, two types of tests were designed to collect performance data in the ITS program. They were

Table 1. Performance Factors and Levels

PERFORMANCE FACTOR	LEVELS
City (Remote terminal site)	San Diego, CA Ft. Worth, TX Seattle, WA Washington, DC Denver, CO
Network	PDN A PDN B PDN C D or F
Day of Week	Monday/Friday Tuesday Wednesday Thursday
Time Period (Local time at remote terminal site)	0830–1000 1000–1130 1330–1500 1500–1630 1900–0100 0100–0700
Block Size (User information transfer tests only)	64 characters 128 characters 512 characters

- access-disengagement tests, which collected data for estimating values of all access and disengagement parameters, and

- user information transfer tests, which collected data for estimating values of all user information transfer parameters (except for the two misdelivery parameters).

Access-disengagement tests consisted of 20 successive data communication sessions. Each such test normally included 20 access trials, 20 source disengagement trials, and 20 destination disengagement trials. In each session, a single 512-character user information block was transmitted to verify successful access.

User information transfer tests consisted of a single data communication session in which a total of 10,240 user information characters were transmitted as a sequence of blocks. Such a test normally included 160, 80, or 20 successive block transfer trials when the block size was 64, 128, or 512 characters, respectively.

Each test consisted of successive trials of the same data communication function rather than randomly arranged trials of different functions. This design was based on practical constraints--once a particular data extraction set-up had been established, it was efficient to conduct many successive trials before changing to a different set-up. Resulting dependence among trials was to be accounted for in the statistical analysis phase of the measurements. The test sample sizes were also based largely on practical considerations (e.g., the space available for on-line storage of extracted performance data), rather than previously stated precision objectives.

3.5 Test Conditions

In general, four principles are used to design an experiment that includes several levels of several factors. They are:

- randomization in assignment of combinations of factor levels to trials so that any factor not taken into account will tend to be averaged and statistical theory can be applied,

- replication or repetition so that random errors are averaged and parameter estimates are as accurate as desired,

- blocking or grouping of factor levels to reduce variability, and

- balance (conducting the same number of tests for each combination of factor levels) so that uniform precision is achieved.

Complete information on factor effects requires that each combination of factor levels be tested at least once (i.e., a factorial experiment). However, practical constraints prevented the application of this ideal design feature. The performance factors and levels specified in Section 3.3 result in 480 (= 5 x 4 x 4 x 6) combinations of factor levels for access-disengagement tests and 1440 (= 480 x 3) combinations of factor levels for user information transfer tests. For both test types, the number of combinations of factor levels was too large to permit the testing of each combination. Hence, the test plan included only selected combinations and no replications (i.e., a fractional factorial experiment).

It was not practical to randomly arrange combinations of factor levels. Limited resources required that all tests from a given remote site be conducted during a single visit (in five working days). Additional constraints were introduced by the need for an operator at the host computer site to manually switch between PDNs.

To simplify switching between PDNs, all tests over a particular network connection during daytime (working) hours were scheduled in a single time period. The network to be used during each time period was determined as follows:

- o The networks were numbered randomly as 0, 1, 2, or 3.
- o The number of the network to be used in the first time period in the day was selected as the day of the month modulo 4. For example, on July 25 testing would start with network 1, followed in order by networks 2, 3, and 0.
- o All tests carried out during a given night would use only a single network--the first network used during the day.
- o Four tests were scheduled for each time period--an access-disengagement test and one user information transfer test for each of the three block sizes specified in Section 3.3.

This gives connections over each network equal coverage in each time period (Monday afternoon and Friday morning are considered a single day). An example of such a test schedule is shown in the following table.

Time of Day	Day of Week			
	Tu	W	Th	F
0830	A	B	C	F
1030	B	C	F	A
1230	C	F	A	B
1430	F	A	B	C

Obviously, this arrangement is not random, but it achieves balance over days and time periods, taking explicit account of the possible systematic effect of time of day. It is, in fact, a common statistical design, the Latin square. The Latin square provides a special kind of blocking; both days of the week and times of day are blocks. Measured values for the many individual trials within each time period cannot be analyzed as independent observations, but the mean for each time period can be taken as the elementary observation and the group of 16 means can be analyzed (by an analysis of variance) for significance of any differences among days and among times of day (Box et al., 1978, pp. 245-255; Appendix H of this report).

Balance is achieved by always using the same number of trials in each access-disengagement test and by transmitting the same number of blocks in each user information transfer test for a given block size. Similarly, the same number of tests is scheduled for each city, network connection, day of the week, time of day, and block size. If just one test in each city fails, the analysis can readily be adjusted. However, if two or more fail, the analysis becomes considerably more complicated, and it may be impossible to separate the effects of factors. Details of the planned test schedules are presented in Appendix F.

4. MEASUREMENT CONDUCT

The overall conduct of the performance measurements is outlined in Figure 4. In the on-line data extraction phase of the measurements, a series of tests was conducted in accordance with the plan described in Section 3. Each test produced a set of binary data files that contained records of all significant events observed at the monitored interfaces during the test.

The post-test processing phase of the measurements consisted of three principal processes. In the data conversion process, extracted performance data for each test were transformed into a prescribed ASCII-character format

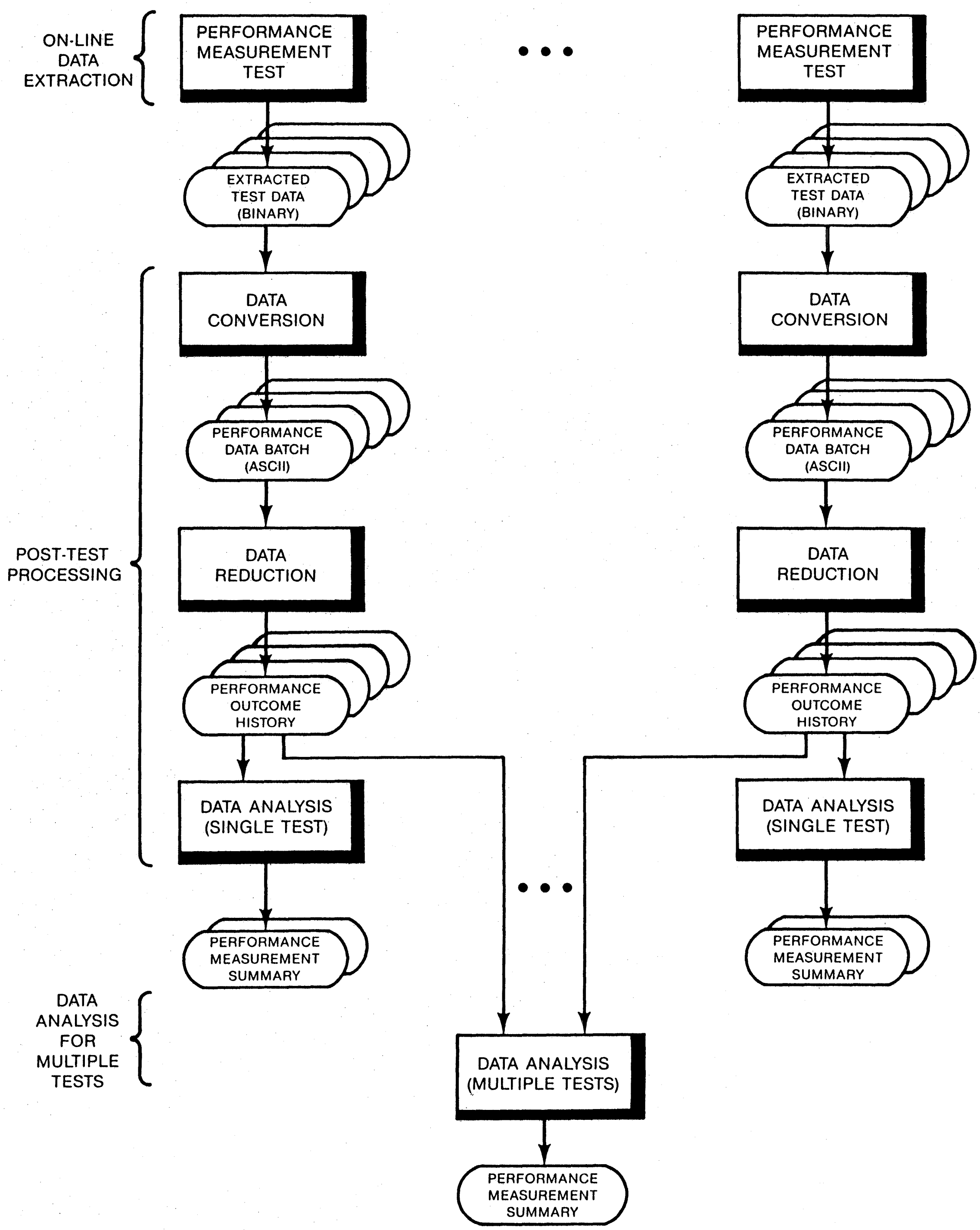


Figure 4. Outline of measurement conduct.

for input to the subsequent reduction process. Data reduction procedures identified individual performance trials and determined their outcomes. The latter were recorded in a set of performance outcome files that served as input to the data analysis process and to data display procedures that generated various plots (e.g., histograms) of delays. The data analysis process for an individual test produced performance parameter estimates and their confidence limits based on that test. As outlined in Section 2.2.6, the post-test processing for a given test was conducted by invoking a shell script with the test number as an argument.

The final phase of the measurements included two types of analysis of multiple tests. In the first, Latin squares of the kind described in Section 3.5 were examined for the significance of any differences among days and among time periods. The second type of analysis produced performance parameter estimates and their confidence limits based on pooled data from selected sets of tests.

Subsections that follow provide a more detailed account of the conduct of the performance measurements. These subsections correspond to the three phases of measurement conduct shown in Figure 4 and briefly outlined above.

4.1 On-Line Data Extraction

The system developed to implement on-line data extraction consisted of a collection of hardware and software elements that established and terminated connections, transmitted and received user information, and recorded significant interface events. This system was then used to conduct a series of tests from the five cities listed in Table 1. Several field trials and preliminary runs were required to establish effective test procedures. The dates and locations of these tests are listed in Table 2.

The discussion of on-line data extraction in this section consists of three parts. The first briefly describes some hardware devices used in the tests, the second summarizes the software, and the third outlines the conduct of a typical data extraction test.

Table 2. Location and Dates for Testing

Date (1983)	Location	Purpose
June 16-23	Denver, CO	First Field Trial
July 25 - August 2	Washington, DC	Preliminary Testing
August 8-17	San Diego, CA	Preliminary Testing
October 17-21	Ft. Worth, TX	Data Collection
December 1-8	Seattle, WA	Data Collection
December 11-15	Washington, DC	Data Collection
December 27-30	Denver, CO	Data Collection

4.1.1 Test Hardware

Major hardware elements involved in a typical test are indicated in Figure 5. No special designs for data extraction devices were required, since all such hardware was available from commercial vendors. The ITS host, located in Boulder, was a WICAT 150-6 desktop microcomputer with a Motorola 68000 CPU chip; it used a Version 7 UNIX™ operating system with Berkeley enhancements. The computer had 256 kilobytes of RAM, a 15 megabyte Winchester disk drive, a 750 kilobyte byte floppy disk drive, 5 asynchronous serial ports, and a graphics console screen and keyboard. A small dot-matrix printer and Hayes 1200 Smartmodem were attached to the machine via a parallel port and one of the serial ports, respectively. The satellite clock receiver and PAD were connected to asynchronous ports. The remote terminal computer was an essentially identically configured WICAT 150-6 system with a similar set of peripherals. This latter system and its peripherals, which weighed about 250 pounds (114 kg), were transported to each of the test sites in several containers.

The remote terminal computer connections to all networks used a 1200 bps modem (Hayes Model 212) with an autodialer that could use either a dual-tone multiple-frequency (DTMF) code or a dc pulse code. The dialed number at some sites depended on the availability of trunking. For example, in Seattle, WA,

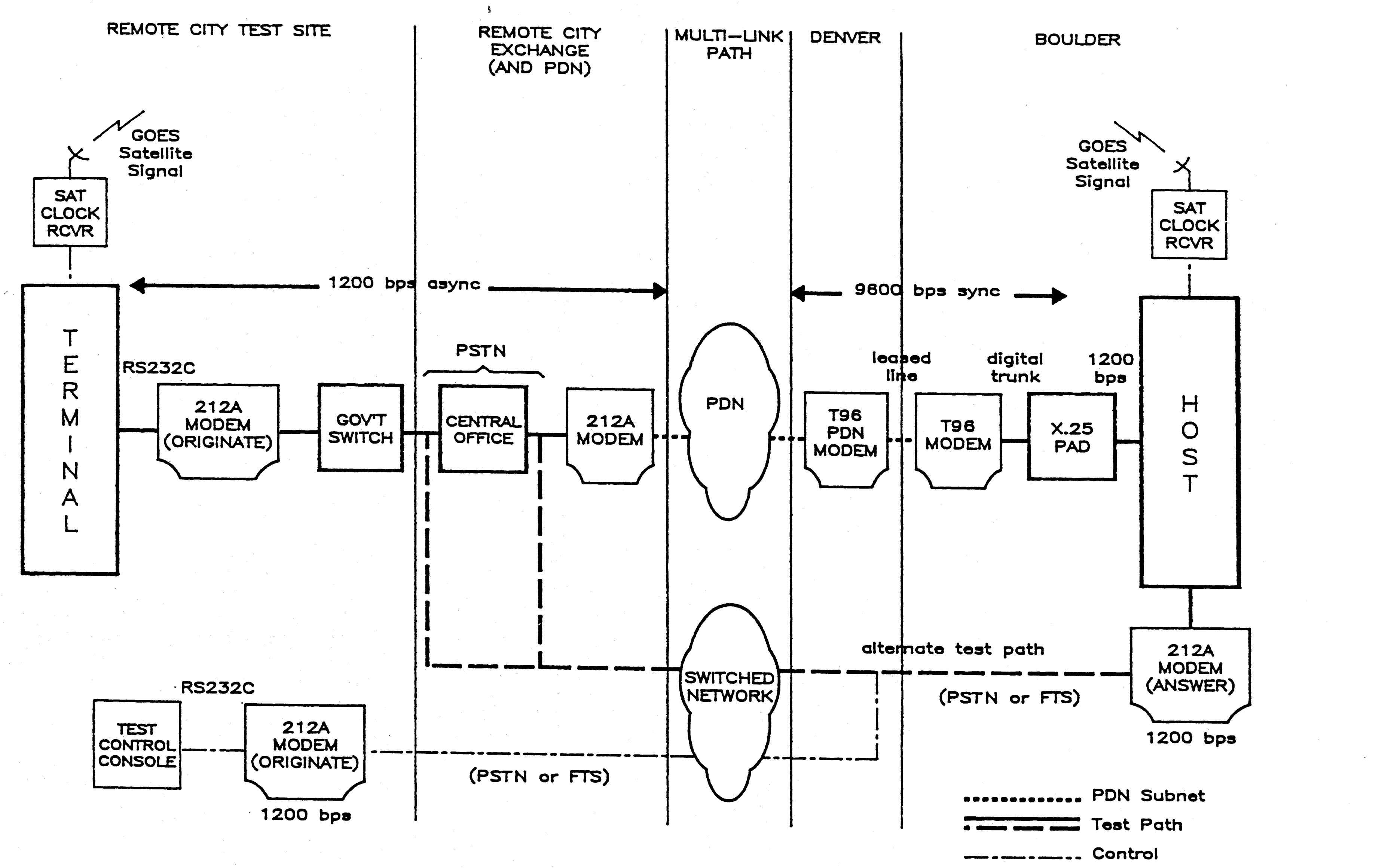


Figure 5. Block diagram of equipment used for conducting tests.

and in Washington, DC, toll trunk calls required the terminal to dial 9 for access to a PDN or the PSTN, and to dial 8 for access to the FTS trunk. When these trunks were used, a 2-second delay was automatically inserted to provide time to receive the trunk dialing tone.

The synchronized time reference required to record interface event times in the ITS tests was provided by the NBS time dissemination service utilizing the Geostationary Operational Environmental Satellite (GOES) (Kamas and Howe, 1979). This service makes it possible to obtain a time signal accurate to within 1 millisecond anywhere in North America. Several vendors supply an antenna/receiver/interface package to obtain time from the satellite. The receiving systems used in the ITS tests consisted of a 1-foot-square active antenna connected via coaxial cable to a compact clock receiver/interface unit. Each clock receiver was equipped with a serial RS-232-C interface that was connected to the local microcomputer test set via standard serial communication cards.

An additional ASCII CRT terminal and a 1200 baud modem with a dial-up connection to the host microcomputer was used in the tests. Under normal conditions, this arrangement allowed a single operator at the remote site to conduct a test without involving personnel in Boulder. Exceptions occurred when a switch had to be changed to permit connection to another PDN or a floppy disk in the host required replacement. All test equipment is concisely summarized in Table 3.

4.1.2 Test Software

The software developed to carry out on-line data extraction consisted of two separate but related sets of computer application programs written in the C language (Kernighan and Richie, 1978). One set, collectively called the XMIT program and installed in the remote terminal computer, served both as the originating (and source) user and the associated interface monitor. The other, called RECV and installed in the host computer, performed analogous activities at the destination interface. These programs thus exemplified the <u>active</u> approach to data communication performance measurement described in Appendix B of ANS X3.141.

The detailed design of on-line data extraction software was facilitated by first constructing a session profile, a concise and comprehensive graphical representation of the data communication process shown in Figure 6. This

Table 3. Equipment Used in Testing

	Item	Features	Quantity	Brand-Model
1.	Microcomputer-UNIX 32 bit, M68000	5 Multiuser, async ports; 512K RAM; 15 MB Winchester; 720KB floppy drive; UNIX Version 7 with Berkeley enhancements.	2	WICAT 150-6
2.	NBS time receiver	GOES satellite antenna & receiver with RS-232C output. Accurate to ± 1 MS.	2	Kinemetrics True Time Model 468-C
3.	Modem 300/1200	Bell 103A, 212A compatable	2	Hayes Smartmodem 1200
4.	X.25 PAD	Packet assembler/ disassembler	1	Dynapac Multiplex 25
5.	Remote CRT	CRT with 1200 band async serial port	1	Radio Shack TRS-100 portable computer
6.	Printer, Dot Matrix	8 1/2 wide printer (10, 12, 16 1/2 char/inch), parallel interface	2	Epson FX-80

figure, which is a more elaborate version of the event sequence diagram in Figure 3, shows the successive functions performed by the participating entities during a typical test on a PDN connection and indicates performance-significant events resulting from those functions. It includes certain performance failures, as well as the normal sequence of activities.

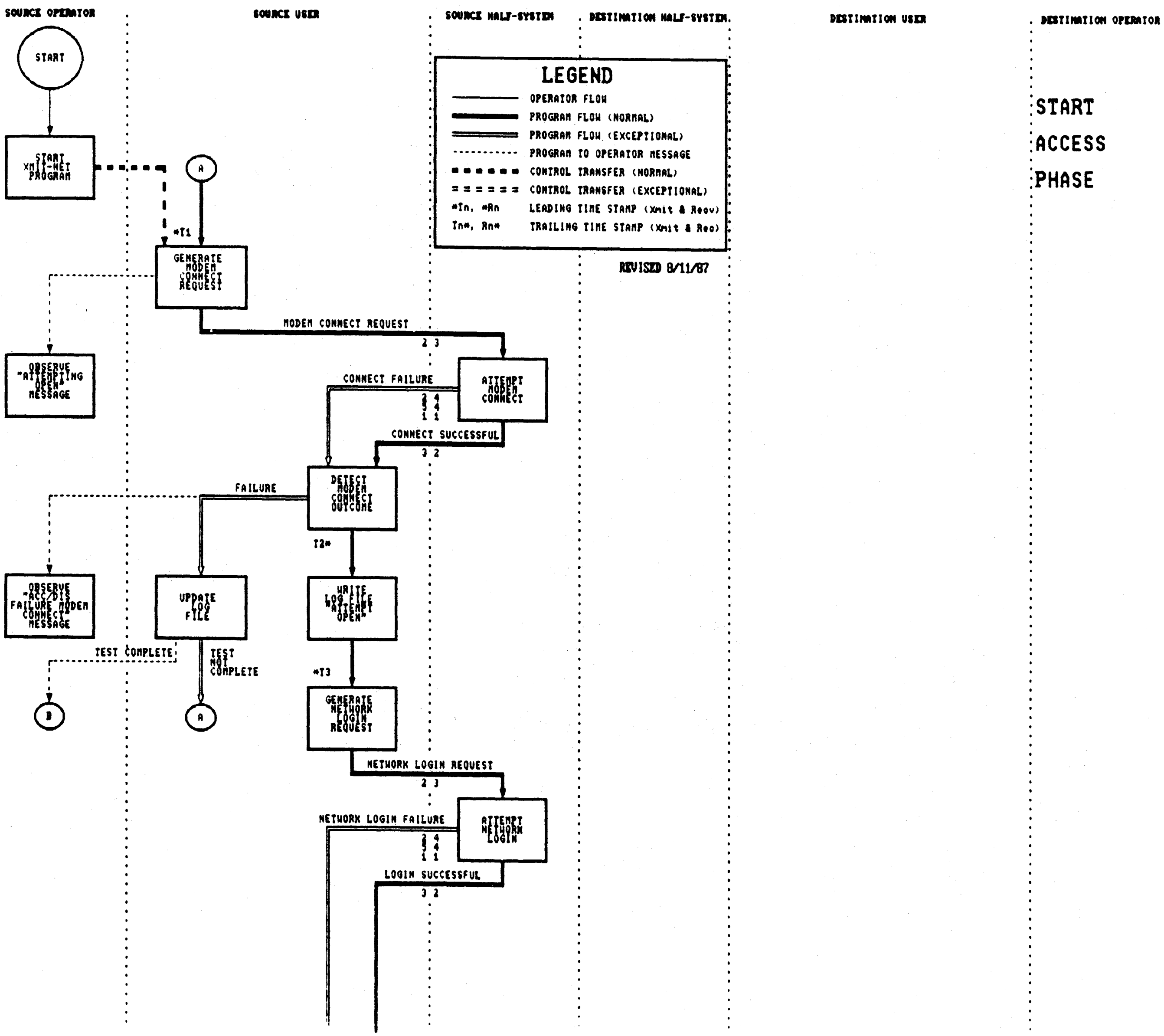
Participating entities are indicated at the top of the diagram. The source and destination half-systems collectively consisted of the PDN and the two computer operating systems. The source and destination users were, respectively, the XMIT and RECV programs. In all tests, the source user was the originating user (i.e., the source user issued all access requests).

Rectangular boxes indicate functions performed by the participating entities. Large circles denote entry and exit points, and small circles denote connect points. Lines indicate actual or potential movement of information or control. Six types of lines are shown:

- o Information Flow (Solid Lines)
  - Heavy (Type 1) - Normal Program Flow
  - Double (Type 2) - Exceptional Program Flow
  - Light (Type 3) - Operator Flow
- o Control Flow (Dashed Lines)
  - Heavy (Type 4) - Normal Control Transfer
  - Double (Type 5) - Exceptional Control Transfer
  - Light (Type 6) - Program-to-Operator Message

Captions accompanying a line describe the nature of the information communicated. During a normal test, all paths on the session profile are followed except for the double lines (Types 2 and 5). A line crossing a user/system interface in Figure 6 corresponds to a performance-significant event. The octal representation of the communication state immediately following such an event is shown in the session profile for each relevant entity. Communication states and their relation to reference events are described in Appendix D.

Clock readings used to obtain event times are shown by the symbols T1, T2, ..., T16 (for the source or transmitting site) and R1, R2, ..., R5 (for the destination or receiving site). Clock readings preceded by an asterisk (e.g., *T1) precede an event and clock readings followed by an asterisk (e.g., R1*) follow an event. In implementing the time-tagging process with the UNIX™ operating system, the clock readings required subsequent correction to obtain the actual event times. This correction was performed during the data


SOURCE OPERATOR
SOURCE USER
SOURCE HALF-SYSTEM
DESTINATION HALF-SYSTEM
DESTINATION USER
DESTINATION OPERATOR
LEGEND
OPERATOR FLOW
PROGRAM FLOW (NORMAL)
PROGRAM FLOW (EXCEPTIONAL)
PROGRAM TO OPERATOR MESSAGE
CONTROL TRANSFER (NORMAL)
CONTROL TRANSFER (EXCEPTIONAL)
*Tn, *Rn LEADING TIME STAMP (Xmit & Recv)
Tn*, Rn* TRAILING TIME STAMP (Xmit & Rec)
REVISED 8/11/87
START
ACCESS
PHASE
START
START XMIT-NET PROGRAM
A
*T1
GENERATE MODEM CONNECT REQUEST
OBSERVE "ATTEMPTING OPEN" MESSAGE
MODEM CONNECT REQUEST
2 3
ATTEMPT MODEM CONNECT
CONNECT FAILURE
CONNECT SUCCESSFUL
3 2
DETECT MODEM CONNECT OUTCOME
FAILURE
T2*
OBSERVE "ACC/DIS FAILURE MODEM CONNECT" MESSAGE
UPDATE LOG FILE
WRITE LOG FILE "ATTEMPT OPEN"
TEST COMPLETE
TEST NOT COMPLETE
B
A
*T3
GENERATE NETWORK LOGIN REQUEST
NETWORK LOGIN REQUEST
2 3
ATTEMPT NETWORK LOGIN
NETWORK LOGIN FAILURE
LOGIN SUCCESSFUL
3 2

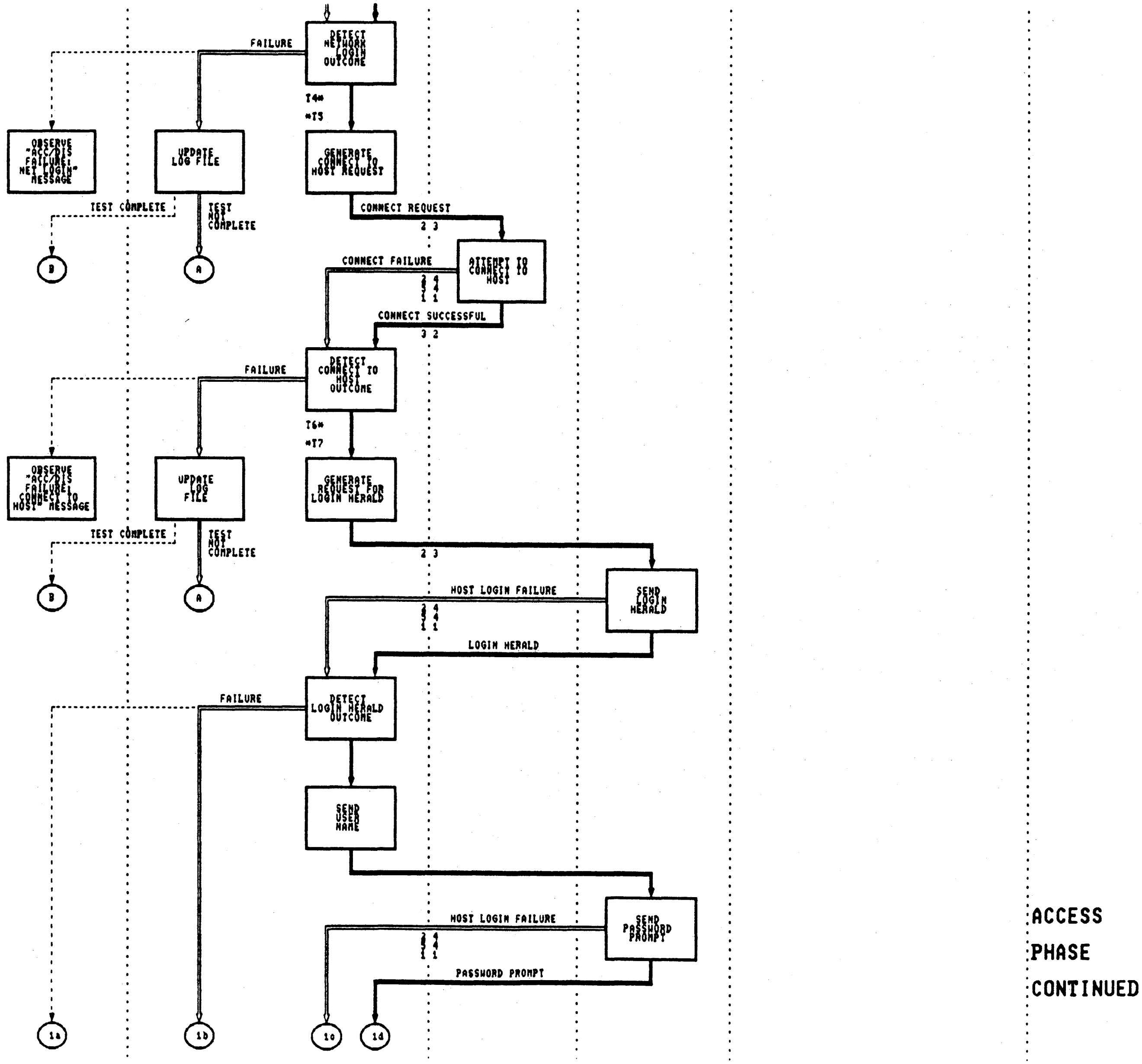
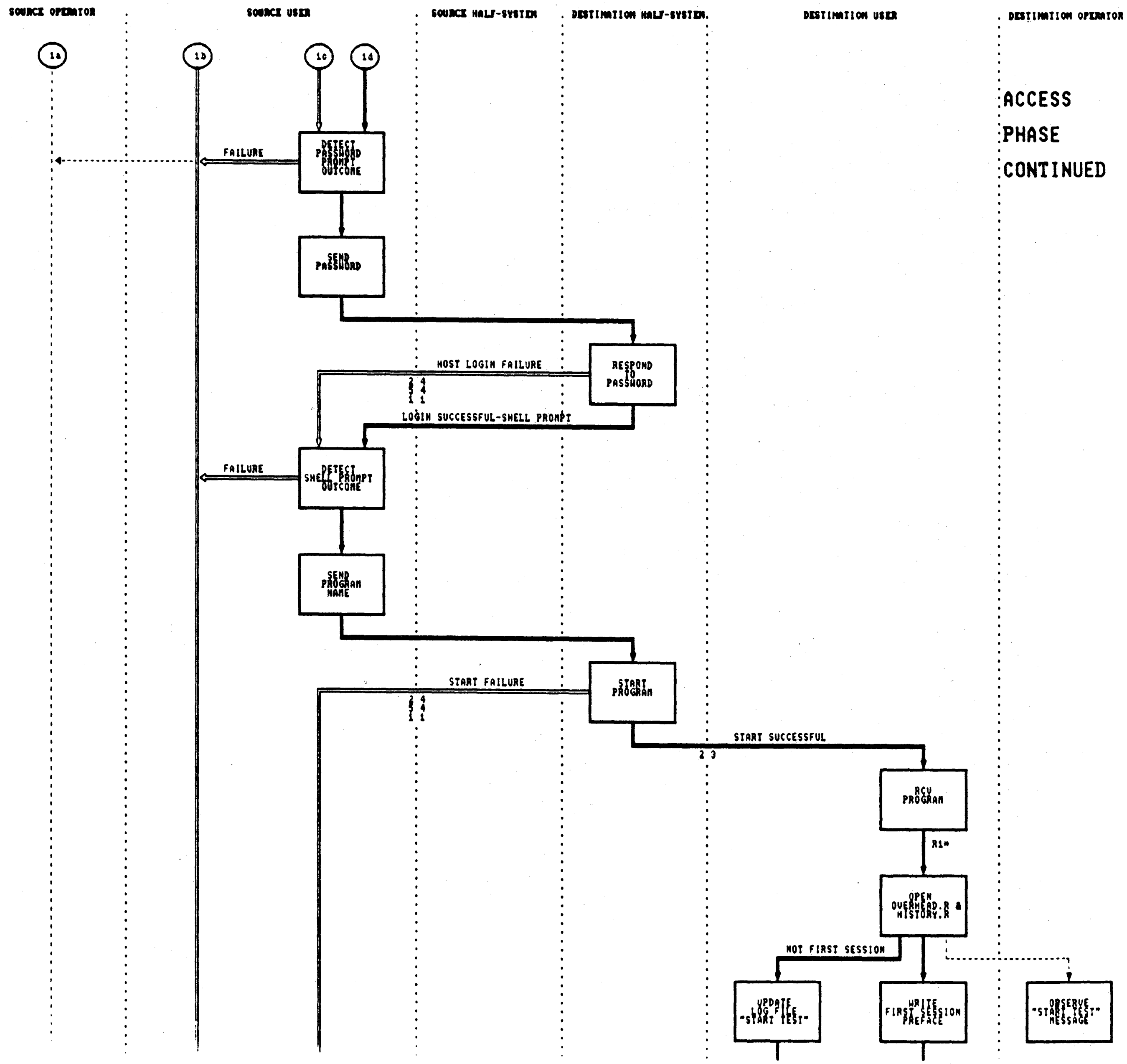


Figure 6 (Part 1). Session profile for tests on a PDN connection.


SOURCE OPERATOR
SOURCE USER
SOURCE HALF-SYSTEM
DESTINATION HALF-SYSTEM
DESTINATION USER
DESTINATION OPERATOR
ACCESS
PHASE
CONTINUED
1a
1b
1c
1d
FAILURE
DETECT PASSWORD PROMPT OUTCOME
SEND PASSWORD
RESPOND TO PASSWORD
HOST LOGIN FAILURE
LOGIN SUCCESSFUL-SHELL PROMPT
FAILURE
DETECT SHELL PROMPT OUTCOME
SEND PROGRAM NAME
START FAILURE
START PROGRAM
START SUCCESSFUL
RCV PROGRAM
R1*
OPEN OVERHEAD.R & HISTORY.R
NOT FIRST SESSION
UPDATE LOG FILE "START TEST"
WRITE FIRST SESSION PREFACE
OBSERVE "START TEST" MESSAGE

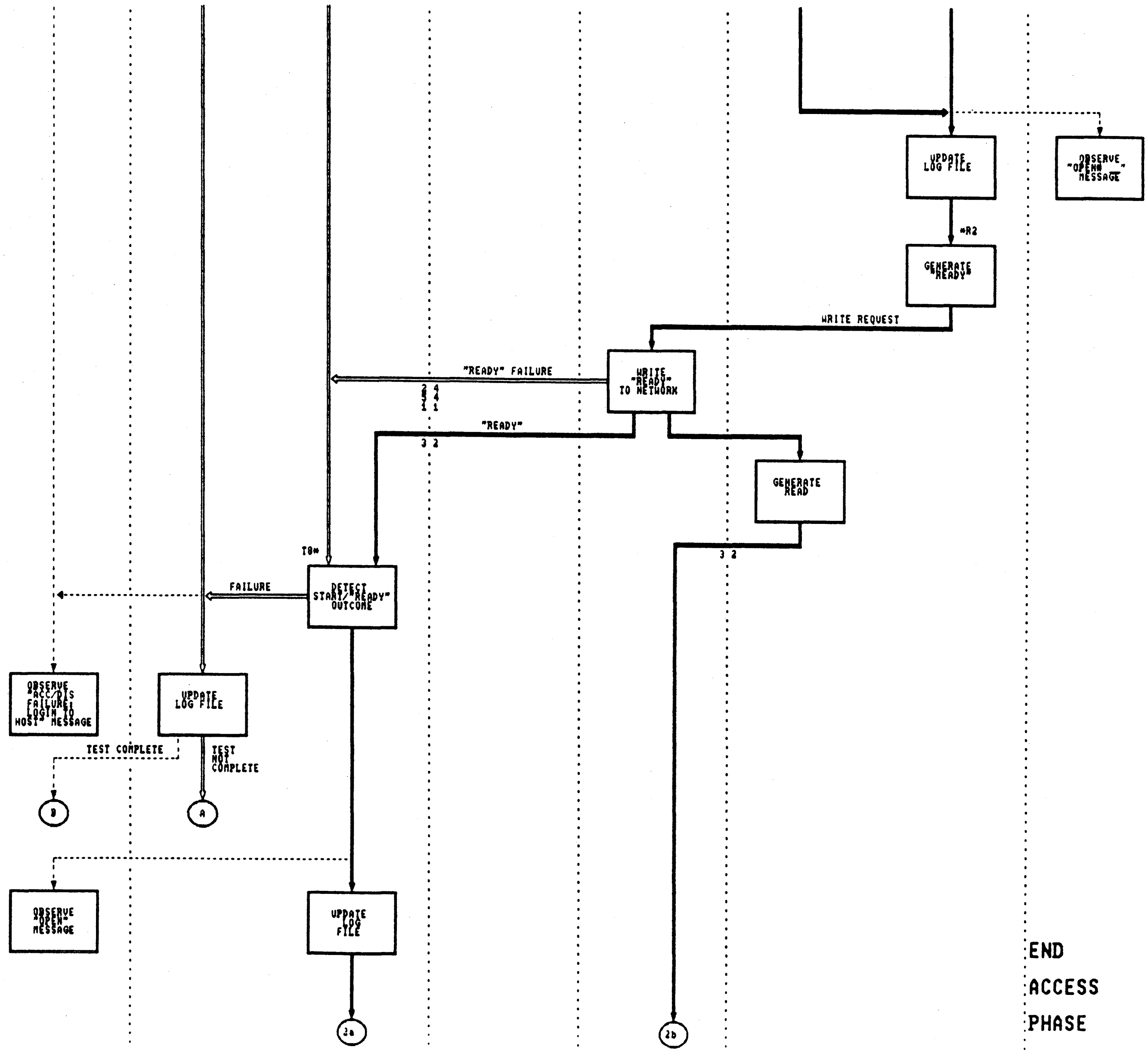
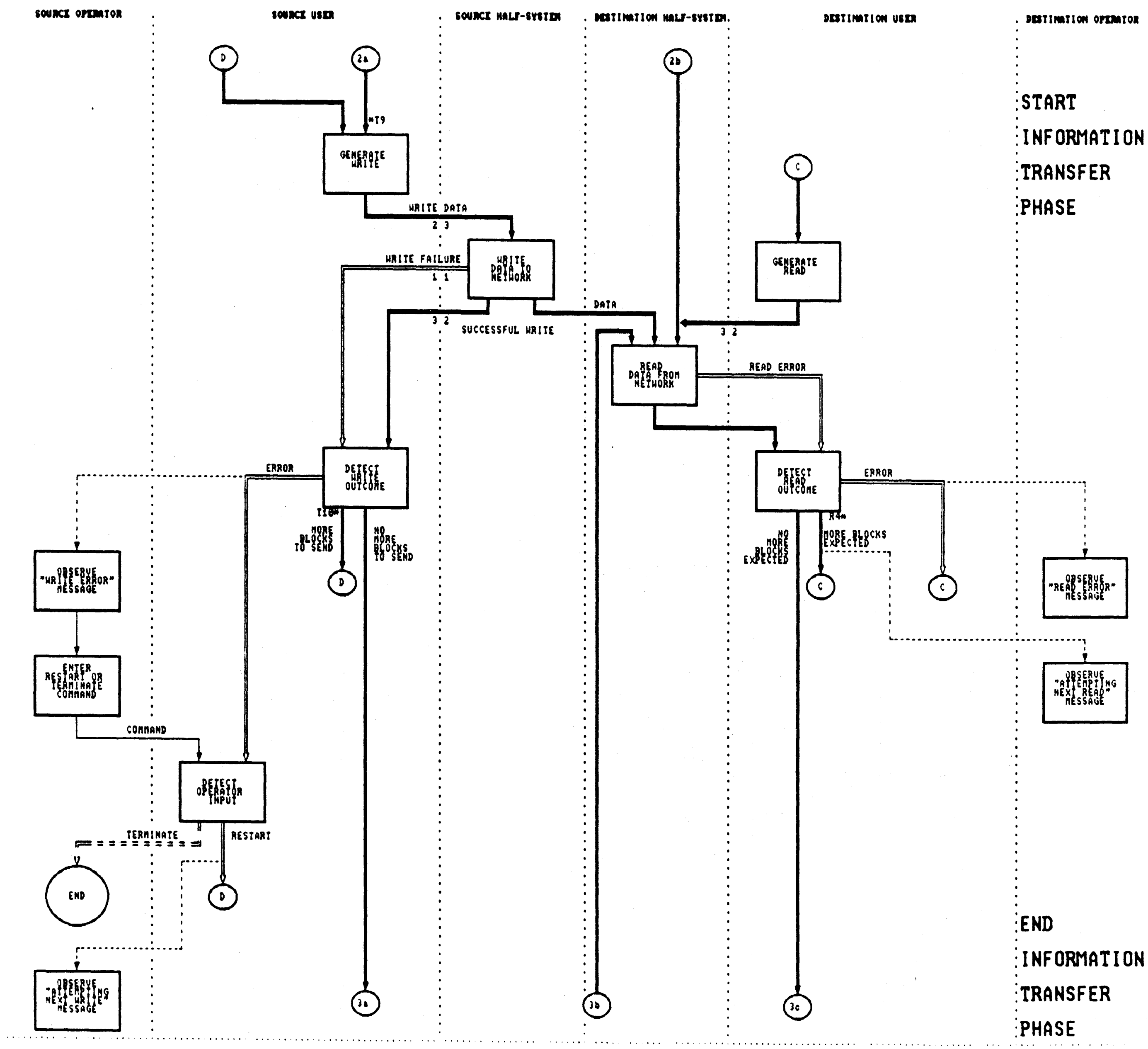


Figure 6 (Part 2). Session profile for tests on a PDN connection.


SOURCE OPERATOR
SOURCE USER
SOURCE HALF-SYSTEM
DESTINATION HALF-SYSTEM
DESTINATION USER
DESTINATION OPERATOR
START
INFORMATION
TRANSFER
PHASE
GENERATE WRITE
WRITE DATA
WRITE DATA TO NETWORK
WRITE FAILURE
SUCCESSFUL WRITE
DATA
GENERATE READ
READ DATA FROM NETWORK
READ ERROR
DETECT WRITE OUTCOME
ERROR
MORE BLOCKS TO SEND
NO MORE BLOCKS TO SEND
DETECT READ OUTCOME
NO MORE BLOCKS EXPECTED
MORE BLOCKS EXPECTED
OBSERVE "WRITE ERROR" MESSAGE
ENTER RESTART OR TERMINATE COMMAND
COMMAND
DETECT OPERATOR INPUT
TERMINATE
RESTART
END
OBSERVE "ATTEMPTING NEXT WRITE" MESSAGE
OBSERVE "READ ERROR" MESSAGE
OBSERVE "ATTEMPTING NEXT READ" MESSAGE
END
INFORMATION
TRANSFER
PHASE

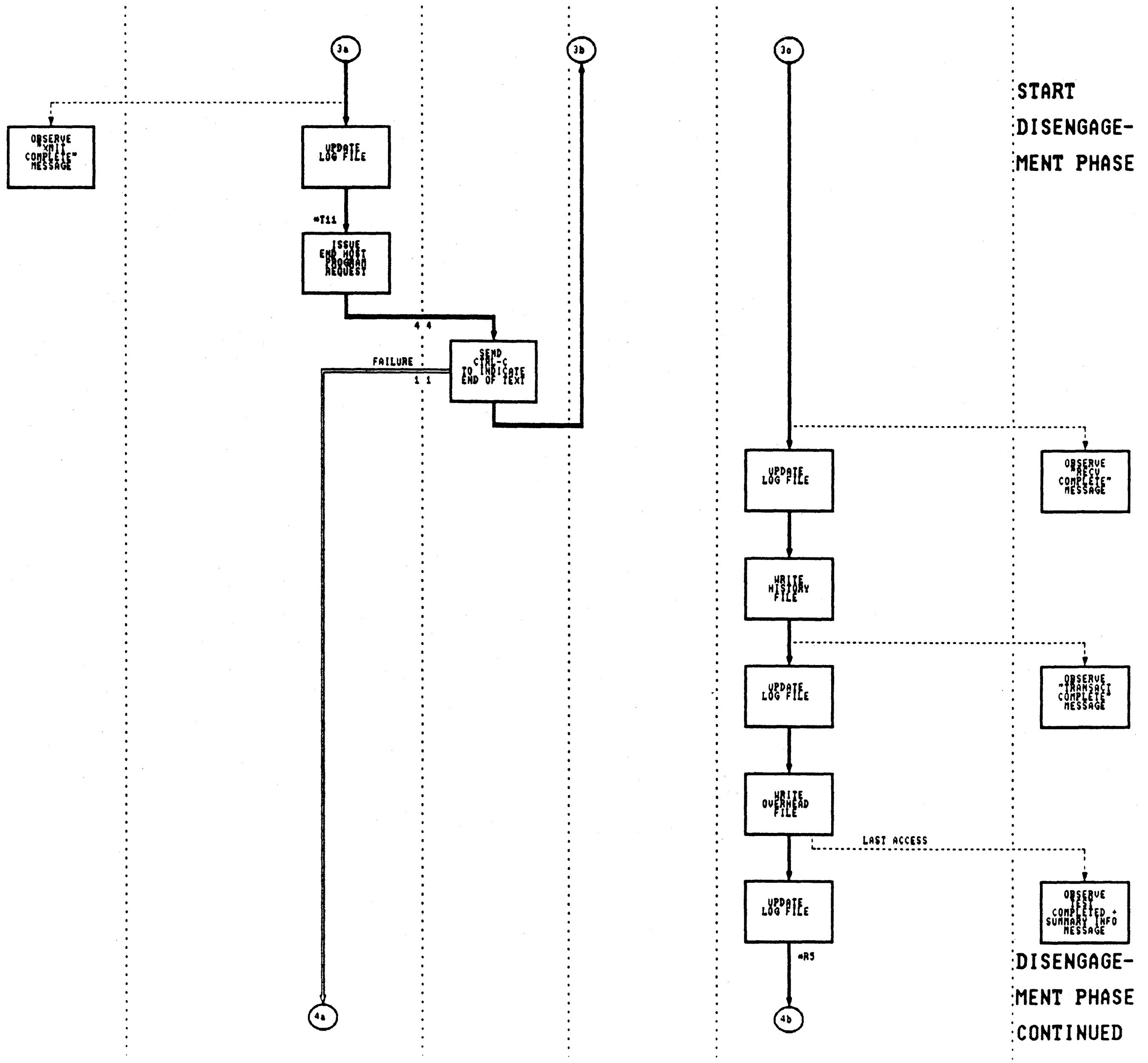
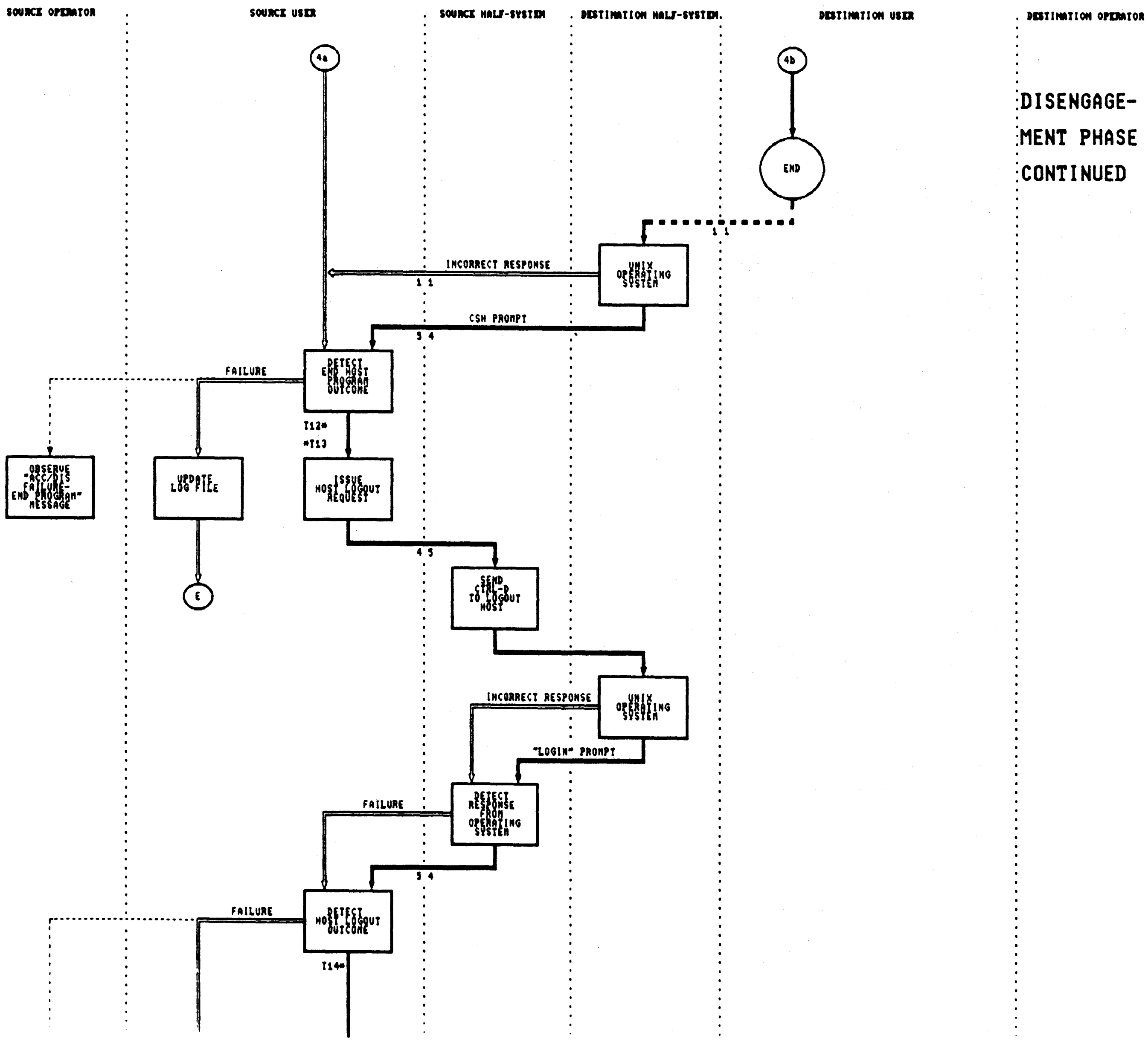


Figure 6 (Part 3). Session profile for tests on a PDN connection.


SOURCE OPERATOR
SOURCE USER
SOURCE HALF-SYSTEM
DESTINATION HALF-SYSTEM
DESTINATION USER
DESTINATION OPERATOR
4a
4b
DISENGAGEMENT PHASE CONTINUED
END
1 1
UNIX OPERATING SYSTEM
INCORRECT RESPONSE
1 1
CSH PROMPT
5 4
DETECT END HOST PROGRAM OUTCOME
FAILURE
T12*
*T13
OBSERVE "ACC/DIS FAILURE- END PROGRAM" MESSAGE
UPDATE LOG FILE
ISSUE HOST LOGOUT REQUEST
E
4 5
SEND CTRL-D TO LOGOUT HOST
UNIX OPERATING SYSTEM
INCORRECT RESPONSE
"LOGIN" PROMPT
DETECT RESPONSE FROM OPERATING SYSTEM
FAILURE
5 4
DETECT HOST LOGOUT OUTCOME
FAILURE
T14*

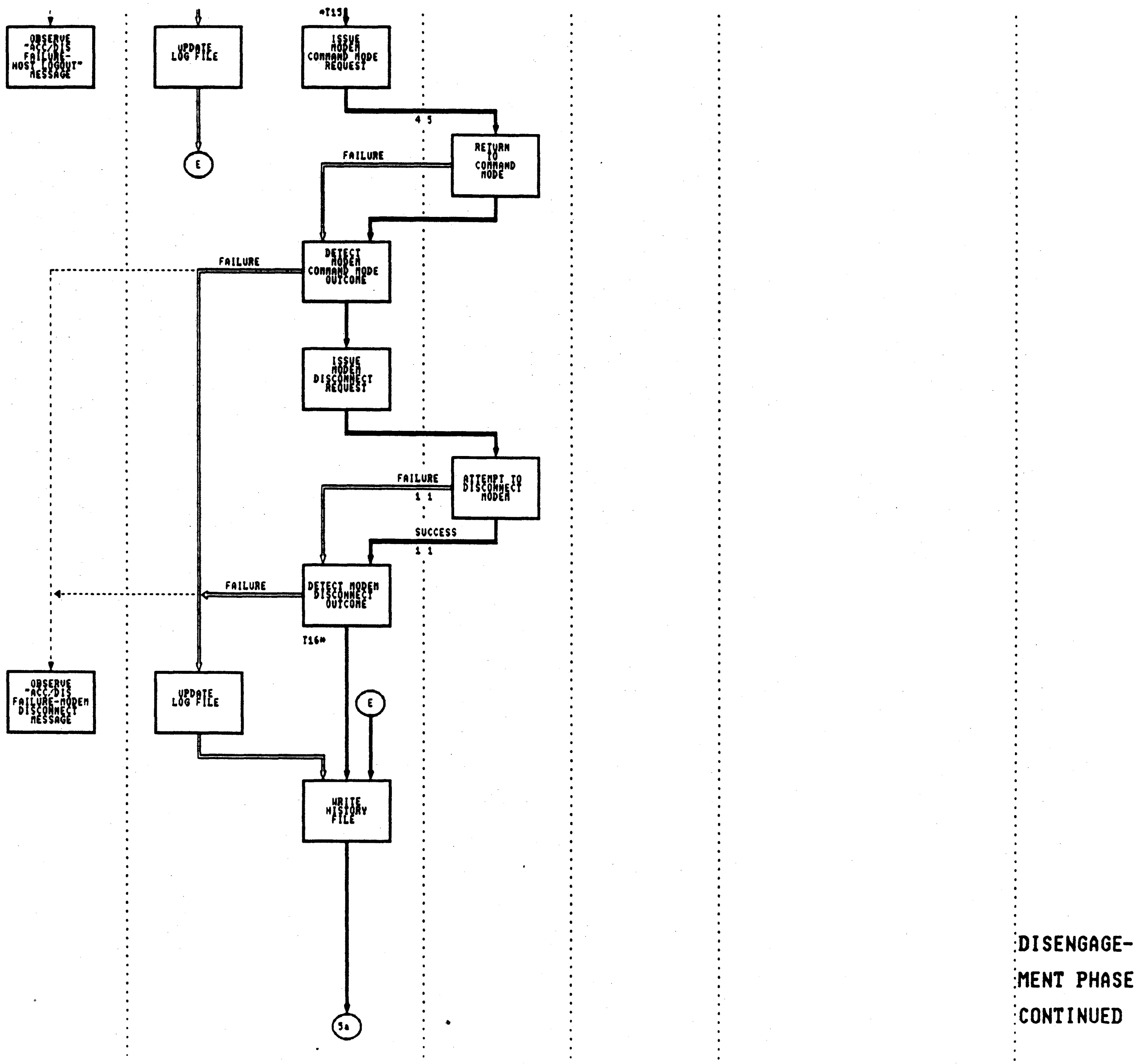


Figure 6 (Part 4). Session profile for tests on a PDN connection.

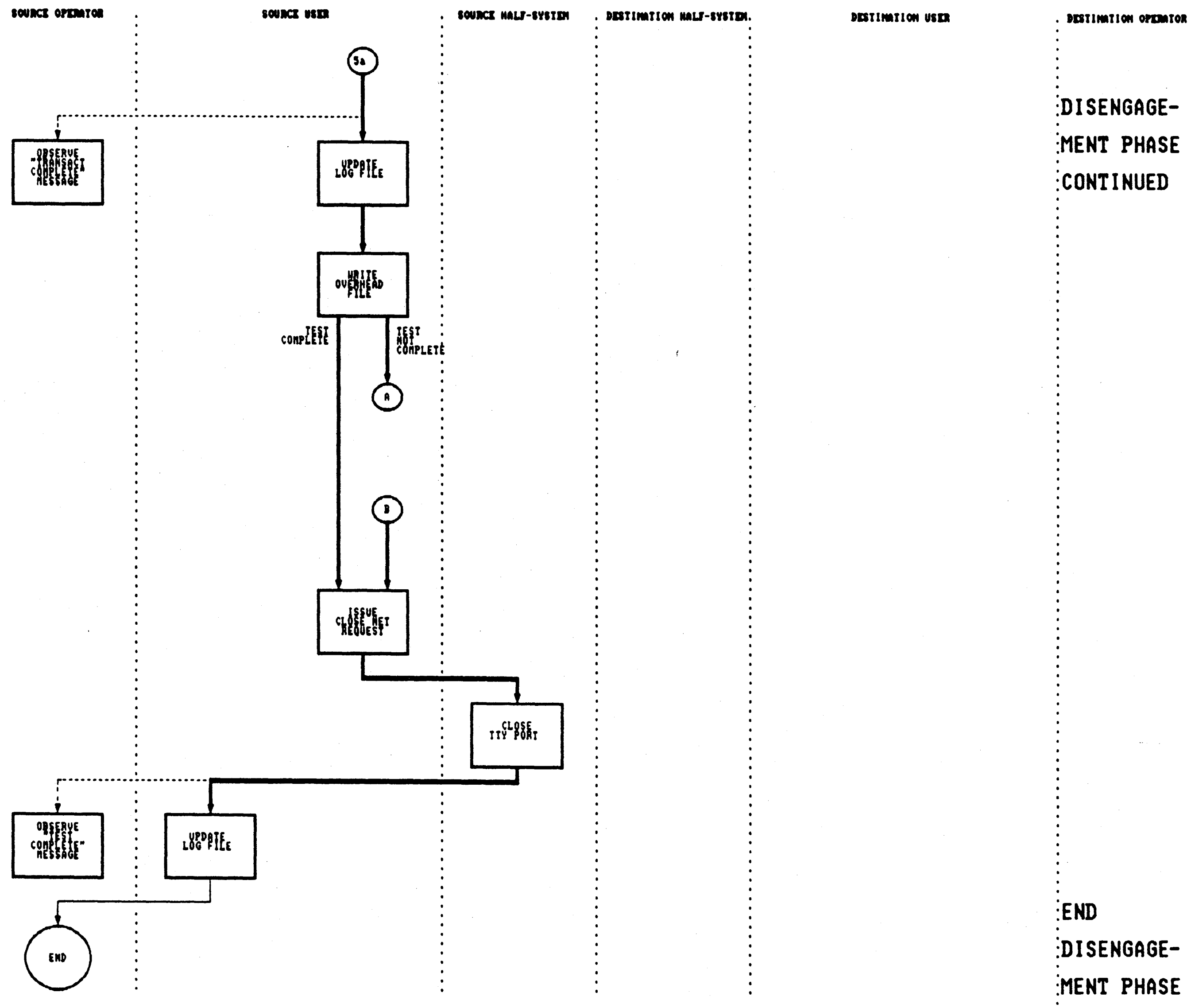


Figure 6 (Part 5). Session profile for tests on a PDN connection.

conversion phase of the data extraction process and is described in Section 4.2.1.

The XMIT and RECV programs executed both access-disengagement and user information transfer tests. Arguments specified at run time (the number of user information blocks to be transmitted in each session, the number of characters in each block, and the number of sessions in the test) enabled the programs to execute a test in the appropriate way. In each session, the XMIT program established connection with the host computer over a selected network, logged into the host and started the RECV program, transmitted a sequence of user information blocks, then logged out and disconnected. Transmitted user information consisted of a pseudorandom sequence of 10,240 ASCII characters; the same sequence was transmitted in all tests. This sequence was generated by XMIT during the initial test from a given location and was stored in a file (DATA.X) for use in subsequent tests.

Connection establishment and termination (i.e., the access and disengagement functions) were accomplished by writing a sequence of commands to the terminal computer's network communications port and observing the output of a corresponding sequence of system responses, as described in detail in Section 3.2. Each command requested the performance of a particular system function (e.g., dialing the local telephone number of a selected PDN) and emulated the action of a terminal operator in establishing or terminating a data communication session with an application program in a distant host. Each system response would ordinarily be displayed on the terminal's screen.

The commands appropriate for a particular test were stored in a <u>protocol file</u>, along with a characteristic segment of the normal system response to each command. Figure 7 shows a protocol file containing the commands and responses for a test on a connection over the Tymnet PDN. The commands and responses in the protocol file were then used by XMIT to carry out the access and disengagement functions. Commands and responses varied from one network to another, so separate protocol files were created for each network. Prior to starting a test, the data extraction software selected the appropriate protocol file. Using protocol files in this way enabled the XMIT program to readily access the different data communication systems employed in the measurements.

The XMIT program generated two event histories for each test. One (named OVERHEAD.X) contained, for each significant event observed at the source interface, a record of the communication states of both local entities (the

```
#     Commands                     Responses
#     -----------------            |  --------------------
#     Tymnet command file for Denver (300/1200 bps)
      ATDT9,8309210\r              |  xx
#     Tymnet command file (300/1200 bps)
*
      A                            |  \sin:\s
*
      \b\xNTIA1;DOC\r              |  ected
*
      \r\d\r                       |  ogin:
      r2d2\r                       |  word:
      password\r                   |  %\s
      recv\s20\s512\s1\s1295\r|       READY
#     logout sequence
*
      \e                           |  %\s
*
      logout\r                     |  in:
*
      +++                          |  \nOK\r\n
      \dATHO\r\dATZ\r              |  \nOK\r\n
```

```
Key to symbols for the sample protocol files:
     #    = Comment, software ignores this line
     *    = Break out of the sequence and return to the calling program
            to obtain time stamps
     \r   = RETURN (decimal (13) ) ^M
     \s   = SPACE (decimal (32) )
     \e   = ETX (End of text:  decimal (3) ) ^C
     \t   = TAB (decimal (9) ) ^I
     \n   = NEWLINE (decimal (10) ) ^J
     \b   = BACKSPACE (decimal (8) ) ^H
     \f   = ACK (decimal (6) ) ^F used for end of text in PC-AT Venix 7
     \x   = CAN (decimal (24) ) ^X used by Tymnet for X-ON, X-OFF
     \d   = BEL (decimal (7) ) ^G used to delay the command for 2 seconds
```

Figure 7. Sample protocol file.

user and the system) immediately after the event and the time read from the satellite clock. These events are described in Section 3.2 and are indicated by a time stamp symbol in the session profile in Figure 6. The other event history (named HISTORY.X) contained, for each transmitted user information block, a record that included the number of characters in the block and the clock time for the Start of Block Transfer event. Text versions of these event histories are illustrated in Figure 8. The RECV program generated an analogous pair of destination event histories (OVERHEAD.R and HISTORY.R). In addition, RECV recorded all user information characters received during the test in a file (DATA.R).

4.1.3 Test Conduct

Prior to the first test at a particular remote terminal site, the dial code in the protocol file for each network was changed so that local calls to the PDNs and direct dial calls via the switched telephone networks would be properly placed through the Government PBX. Preface files containing test descriptors were also edited to correctly identify the city in which the remote terminal was located.

Before running each test, equipment was checked to assure that modems, telephone lines, cable connections, and clocks were functioning properly. System clocks in both the remote terminal and host computers were set by a program that read the satellite clock, then immediately set the system clock to the same time (to the nearest second).

To simplify operator procedures and minimize errors, each test was executed by invoking a UNIX™ shell script, called RUNX, with appropriate arguments. Arguments for the RUNX command specified the test type (access-disengagement or user information transfer), the block size (64, 128, or 512 characters), and the network to be used. A pair of optional arguments specified the delay between the end of one session and the start of the next, and the delay before the XMIT program continued after a user information block was written to the network. When nonzero, these delays were implemented by SLEEP system calls.

The RUNX shell script carried out several preliminary procedures prior to starting the XMIT program. It first checked the number and validity of the arguments entered, informing the operator and terminating the test if an error was detected. It also translated the test type and block size into the number

```
Overhead-information files:

Perfor. measur. ID          = NTIA - PDN test from Washington,
Run number                  =  986
Type                        = Source
Information ID              = User
Source                      = NTIA - Term2 (NBS-Gaithersburg)

Destination                 = NTIA - Host1 (Boulder)
Mo/Day/Yr                   = 12/15/83
Start time (Hr:Min:Sec) =  4: 0:35

  Data from file    ovh.x986


        Record Code  Clock time

          1    23   04:00:35.209
          2    32   04:00:51.770
          3    23   04:00:51.770
          4    32   04:00:52.334
          5    23   04:00:52.334
          6    32   04:00:55.259
          7    23   04:00:55.259
          8    32   04:01:19.459
          9    23   04:01:19.606
         10    32   04:01:23.582
         11    45   04:01:23.736
         12    54   04:01:28.034
         13    45   04:01:28.034
         14    54   04:01:30.525
         15    45   04:01:30.525
         16    54   04:01:36.135
         17    45   04:01:36.135
         18    11   04:01:36.472

                     ...

          1    23   04:37:06.026
          2    32   04:37:23.008
          3    23   04:37:23.008
          4    32   04:37:23.571
          5    23   04:37:23.571
          6    32   04:37:26.404
                     ...
         16    54   04:38:06.373
         17    45   04:38:06.373
         18    11   04:38:06.532
Total # times = 347
```

a. Text Version of OVERHEAD.X File

```
History-information files:

Perfor. measur. ID          = NTIA - PDN test from Washington,
Run number                  =  986
Type                        = Source
Information ID              = User
Source                      = NTIA - Term2 (NBS-Gaithersburg)

Destination                 = NTIA - Host1 (Boulder)
Mo/Day/Yr                   = 12/15/83
Start time (Hr:Min:Sec) =  4: 1:19

  Data from file    his.x986

**File prefix (dd-hhmm) = 15-0401

        Record Bytes Start time     End time

          1    512  04:01:19.606   04:01:23.582
          1    512  04:03:13.670   04:03:19.236
          1    512  04:07:14.243   04:07:19.274
          1    512  04:09:10.832   04:09:15.866
          1    512  04:11:03.589   04:11:08.622
          1    512  04:12:58.437   04:13:04.004
          1    512  04:14:52.478   04:14:56.456
          1    512  04:16:44.494   04:16:50.059
          1    512  04:18:38.466   04:18:42.965
          1    512  04:20:32.731   04:20:38.297
          1    512  04:22:29.129   04:22:33.106
          1    512  04:24:22.704   04:24:28.269
          1    512  04:26:16.711   04:26:21.743
          1    512  04:28:12.849   04:28:16.826
          1    512  04:30:08.865   04:30:13.897
          1    512  04:32:02.805   04:32:06.781
          1    512  04:33:58.546   04:34:02.528
          1    512  04:35:52.892   04:35:57.926
          1    512  04:37:48.400   04:37:52.377
```

b. Text Version of HISTORY.X File

Figure 8. Text versions of extracted event histories.

of blocks per session and the number of sessions (access attempts) per test to be used as arguments to XMIT. The final preliminary procedure was selecting the appropriate protocol file for the test and appending the proper arguments to the RECV command in that file.

The RUNX shell script then called the XMIT program to carry out on-line data extraction. After XMIT was started, output to the screen enabled the operator to observe the progress of the test. Figures 9a and 9b show the respective displays produced on the remote terminal screen when running an access-disengagement test and a user information transfer test. The remote terminal screen display was also written to the LOG.X file. Similar displays were produced at the host site and written to the LOG.R file.

RUNX concluded by calling a shell script (MOVEX) to store test data files in another subdirectory, append the test number to each file, and generate a checksum file for the test data. When execution of RUNX ended, the operator logged into the host computer and invoked a shell script (MOVER) that carried out analogous procedures on received data files.

The final step in conducting a test was the consolidation of test data into one computer. This was accomplished by using the UNIX™ UUCP utility (UUCP is an acronym for UNIX™-to-UNIX™ copy program). The checksum files generated by the MOVEX and MOVER shell scripts were transferred with the data files. When data conversion (described in the next section) was performed later, local checksums were generated and compared with the checksums created by MOVEX and MOVER. Matching checksums assured the integrity of the transferred data.

4.2 Post-Test Processing

As outlined earlier, the post-test processing phase of the performance measurements consisted of three principal processes: data conversion, data reduction, and data analysis (for an individual test). Each of these processes is described in more detail in the subsections that follow.

For a given test, all of the above processes were carried out by invoking a shell script (named DO) with the test number as an argument. The DO shell script directly or indirectly called all other processing software modules, as well as several UNIX™ utilities. These modules included a hierarchy of 20 subordinate shell scripts, 18 C programs, and 4 FORTRAN programs. The UNIX™ utilities, along with several special C programs, were used to extract and

```
-----------network transmission-----------------From:  wdc via: PDN-C
Start test 915 (Satellite time = 16.10:54        Mon Dec 16:10:54 1983


1 blocks of 512 bytes to be sent for each of 20 accesses, = 10240 total bytes
Attempting open #1, Opened, Xmit complete, Transaction complete
Attempting open #2, Opened, Xmit complete, Transaction complete
Attempting open #3, Opened, Xmit complete, Transaction complete
Attempting open #4, Opened, Xmit complete, Transaction complete
Attempting open #5, Opened, Xmit complete, Transaction complete
Attempting open #6, Opened, Xmit complete, Transaction complete
Attempting open #7, Opened, Xmit complete, Transaction complete
Attempting open #8, Opened, Xmit complete, Transaction complete
Attempting open #9, Opened, Xmit complete, Transaction complete
Attempting open #10, Opened, Xmit complete, Transaction complete
Attempting open #11, Opened, Xmit complete, acc/dis failure: modem disconnect
Attempting open #12, Opened, Xmit complete, acc/dis failure: net login
Attempting open #13, Opened, Xmit complete, Transaction complete
Attempting open #14, Opened, Xmit complete, Transaction complete
Attempting open #15, Opened, Xmit complete, Transaction complete
Attempting open #16, Opened, Xmit complete, acc/dis failure: net login
Attempting open #17, Opened, Xmit complete, Transaction complete
Attempting open #18, Opened, Xmit complete, acc/dis failure: net login
Attempting open #19, Opened, Xmit complete, Transaction complete
Attempting open #20, Opened, Xmit complete, Transaction complete

8704 characters at 13926 baud
test completed                                   Mon Dec 12  6:50:56 1983

-----------
Transmitted checksum Matches
```

a. Access—Disengagement Test

```
------------network transmission-------------- From:  wdc via:  PDN-C
Start test 914 (Satellite time = 16.04:04)     Mon Dec 12 16:04:04 1983

20 blocks of 512 bytes to be sent for each of 1 accesses, = 10240 total bytes
Attempting open #1, Opened, Xmit complete, acc/dis failure: modem disconnect

10240 characters at 819 baud
test completed                                 Mon Dec 12 16:06:34 1983

------------

Transmitted checksum Matches
```

b. User Information Transfer Test

Figure 9. Displays on console of remote test computer.

reformat data output by one processing program to serve as input to a subsequent program. The linkage programs greatly facilitated the processing of test data by eliminating operator involvement in the editing and transfer of data files between the conversion, reduction, and analysis programs. The automation of file editing and transfer also prevented the occurrence of errors in these procedures.

4.2.1 Data Conversion

The data conversion process, which prepared extracted performance data for input to the subsequent data reduction process, was accomplished in two principal steps. The first produced corrected values of recorded event times, and the second produced a set of ASCII-text event history files.

The correction of event times obtained from the satellite receiver clock and recorded in the OVERHEAD and HISTORY files depended on whether the clock reading preceded or followed the corresponding interface event. In the ITS tests, clock readings that preceded an interface event were corrected by +120 milliseconds and readings that followed an event were corrected by -13 milliseconds. The event time corrections were performed by a program called TWEAK. This program read the binary data files, corrected the event times, and wrote the corrected times to files with the same format as the original data files. A complete description of the procedure used to determine event time corrections is presented in Appendix D of NTIA Report 81-112 (Wortendyke et al., 1982).

The production of ASCII-text event history files for input to the reduction process was carried out by two programs as outlined in Figure 10. The first, called REFORM, produced the source overhead information file (FORT.14) and destination overhead information file (FORT.15) from binary data in the corresponding OVERHEAD files output by the TWEAK program. Each overhead information file consisted of preface data followed by a sequence of event records.

The second program, called MERGE, produced the source user information file (FORT.17) and destination user information file (FORT.18) from the corresponding HISTORY and DATA files. For each transmitted user information block, MERGE obtained the block transfer start time and the block size from the HISTORY.X file, then extracted the transmitted (ASCII) characters from the DATA.X file. Transmitted data were converted to a machine-independent

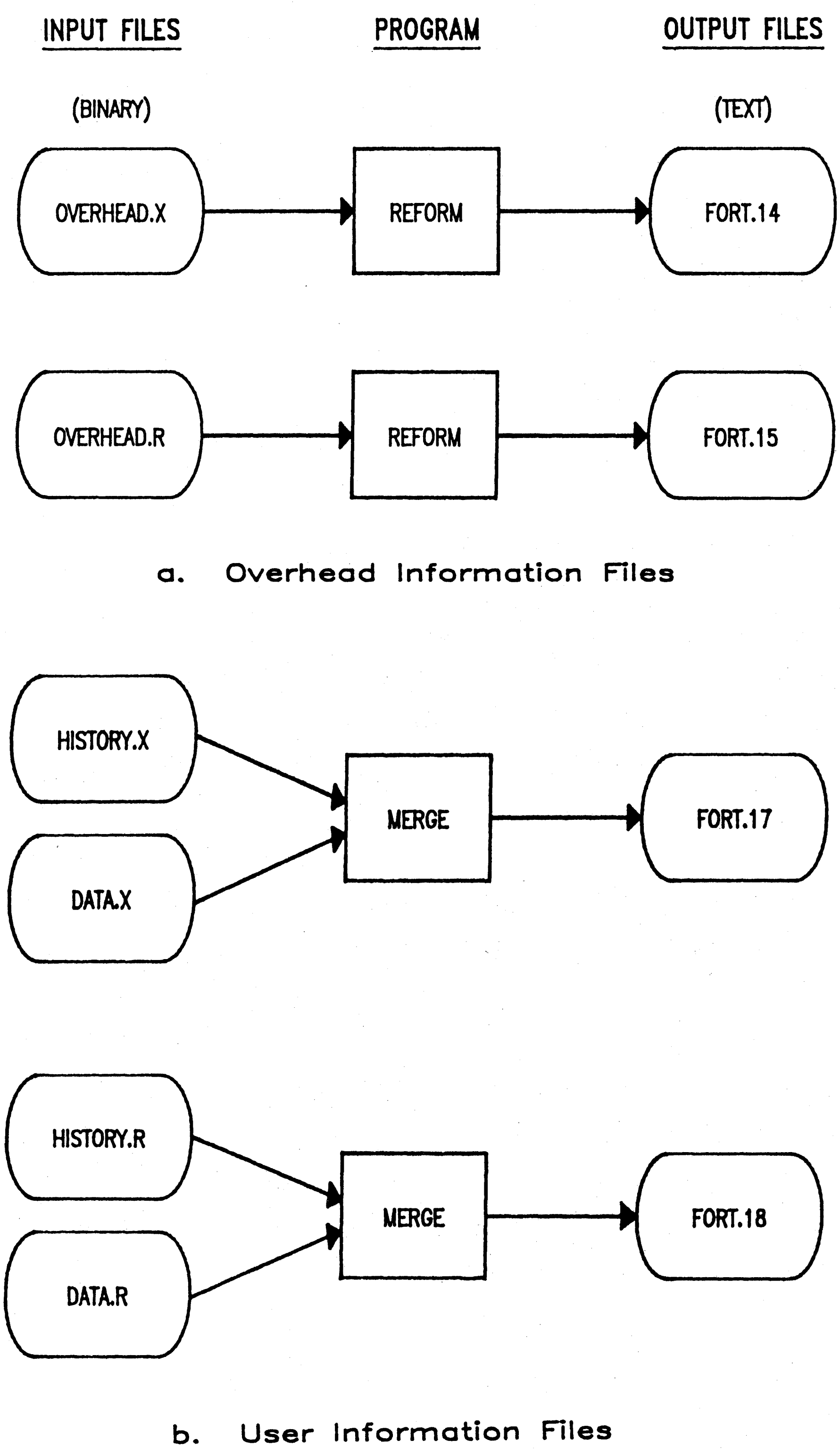


Figure 10. Generation of ASCII files for data reduction.

ASCII-character representation as follows. The binary representation of the transmitted characters was divided into a sequence of 15-bit strings as shown in Figure 11. The last string in the block was completed, if necessary, with binary zero fill. Each string was regarded as the binary representation of a decimal integer, where the bit of lowest index is the most significant bit. The user information block was thus mapped into a sequence of decimal integers in the range 0-32,767. The digits for each integer were stored in a user information record as an ASCII-character string right-justified in a 5-character field with zero fill on the left. These records were included in the source user information file, along with block descriptors (e.g., block size and block transfer start time). In a separate run, MERGE executed the analogous procedures for each received user information block and wrote the results to the destination user information file.

Collectively, the overhead and user information files associated with a given test were called a performance data batch. Samples of overhead and user information files are shown in Figure 12. Converting the binary form of extracted performance data to the ASCII-character form described above eliminated machine dependence from the data formats, and enabled the use of system independent software to perform data reduction and analysis.

4.2.2 Data Reduction

The data reduction process for a test identified individual performance trials and determined their outcomes. A simplified outline of this process is shown in Figure 13. Input to the process consisted of the performance data batch generated by the data conversion process and a set of user-defined reduction specifications. The latter included the specified primary and ancillary parameter values used by reduction routines to classify outcomes of performance trials in accordance with ANS X3.102.

Data reduction procedures were carried out by a sequence of three main FORTRAN computer programs: PROLOG, ANALYZ, and EPILOG. An execution of this sequence, which processed a given performance data batch, was called a data reduction run. Each main program implemented a distinct phase of tne reduction process.

In the first phase, PROLOG carried out a preliminary examination and consolidation of input data. The program began by subjecting reduction specifications and extracted performance data to a series of validity checks.

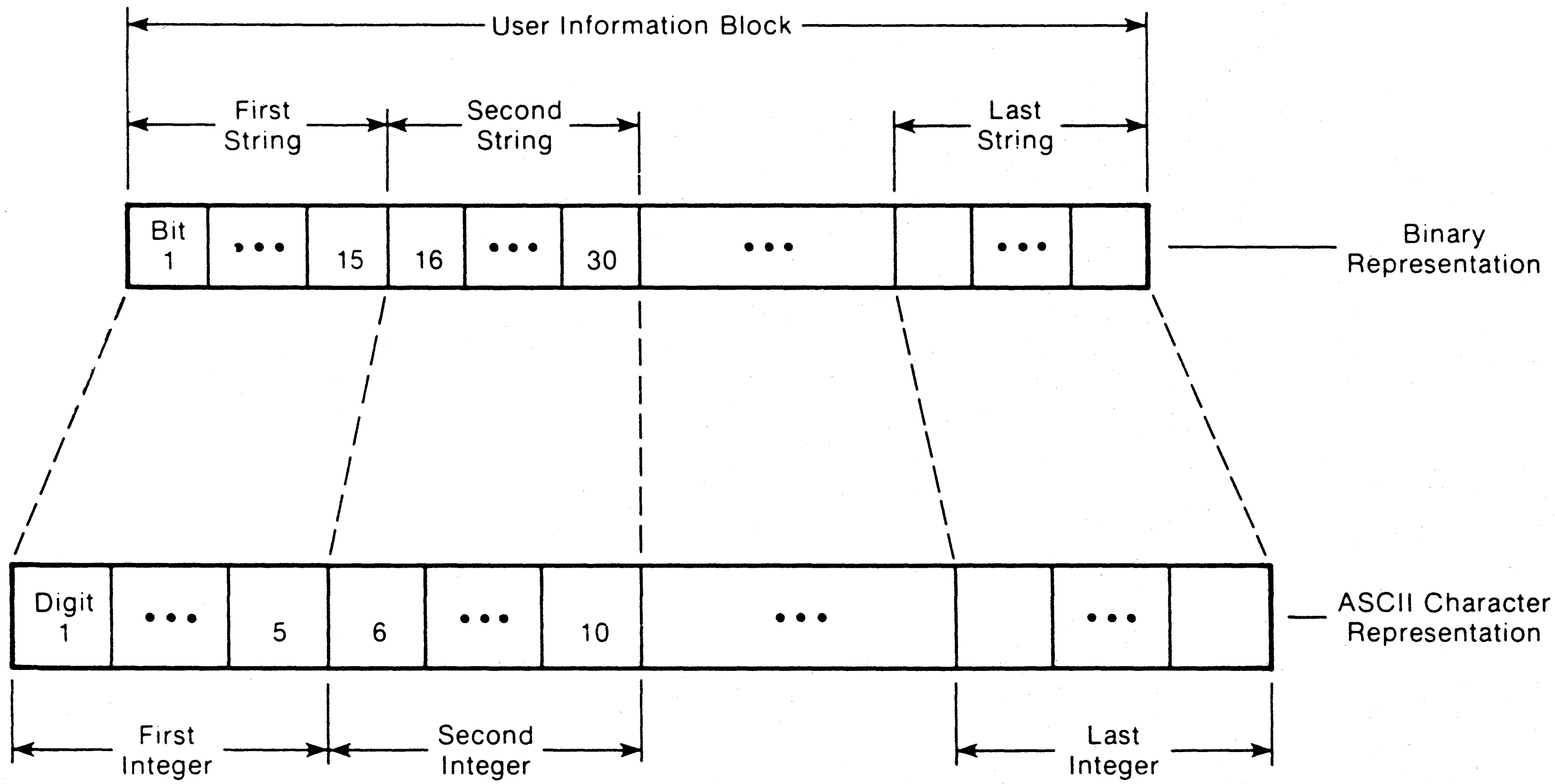


Figure 11. Binary and ASCII-character representations of user information.

```
NTIA - PDN test from Washington,                    0986Source      User

NTIA - Term2 (NBS-GaithersNTIA - Host1 (Boulder)    11    50000.111831215

000000014435329237 7
```

```
0000000144353292377
0000000144517573277
0000000144518902377
0000000144523213277
0000000144524542377
0000000144552463277
0000000144553792377
0000000144794463277
0000000144797262377
0000000144835693277
0000000144838564477
0000000144880215477
        ...
        ...
        ...
0000000165525423277
0000000165530122377
0000000165579133277
0000000165582004477
0000000165625515477
0000000165626844577
0000000165649925477
0000000165651254577
0000000165713525477
0000000165714854577
0000000165715101177
0000000166261462377
0000000166429953277
0000000166431282377
0000000166435583277
0000000166436912377
0000000166463913277
0000000166465242377
0000000166682413277
0000000166685202377
0000000166723643277
0000000166726514477
0000000166775995477
0000000166777324577
0000000166800655477
0000000166801984577
0000000166863605477
0000000166864934577
0000000166865191177
          -999990000
```

a. Source Overhead Information File (FORT.14)

```
NTIA - PDN test from Washington,                  0986Source      User

NTIA - Term2 (NBS-GaithersNTIA - Host1 (Boulder)   831215

0000001.0000001.0004096.00000001447972600000001447972610000000000000000000000000
0616804428186620958708905208370072016705088680443311887018470669818713032101 2359
0911207501263462226211057167130834612360111841947611727007890889918632278181 8742
1397903470032080552505010104491918427953134770436626376223722100928045282762 9026
0912123956271750127027282022490727015212097872063210831092381901723753027022 7473
1539223133271183057900546228892631630061138520732218694299431270620801181302 7443
1245221723026380131721393186491806827250102662152603146220700911327013053621 9026
1488024156106990941222914074522479426939132282383518893016862334608616283403 0515
       ...
       ...
       ...
1285821964283980957427434166011249420035111690340917990100392086620953088083 0263
0706803676282012602321186248850225028534110440673327213263750707316841292982 4885
0836304246192722168300570240042990822833094022063412012216210875423013124481 9534
1488423057035621818217026116962679018489092452018627980262942959317864278581 9012
1310722746271422237521162085810995626742064530770911885136670498726065221722 1099
1155919922032383046712955228851965629527102930347219144101170703321957170981 7996
1375522796197250171813234239930379021558141322396109798213802937012677169922 2865
1564206299280710088412922145283034822595143740712412040057811899517853221702 8784
1270803532198171371819297278690727030263136130551603304099720863406549103902 9816
1092404442121082162205066084050368428009131131960303501300382749813524303062 0027
1400103220117201002220890106451758027509089862011719719058790501814813201702 1830
1450823379281700963625011137330838621580100082153118088132031730619813258342 2096
1564200000000000000000000000000000000000000000000000000000000000000000000000 0000
0000019.0073729.0004096.00000001666852000000001666852020000000000000000000000000
```

b. Source User Information File (FORT.17)

Figure 12. Typical overhead and user information files.

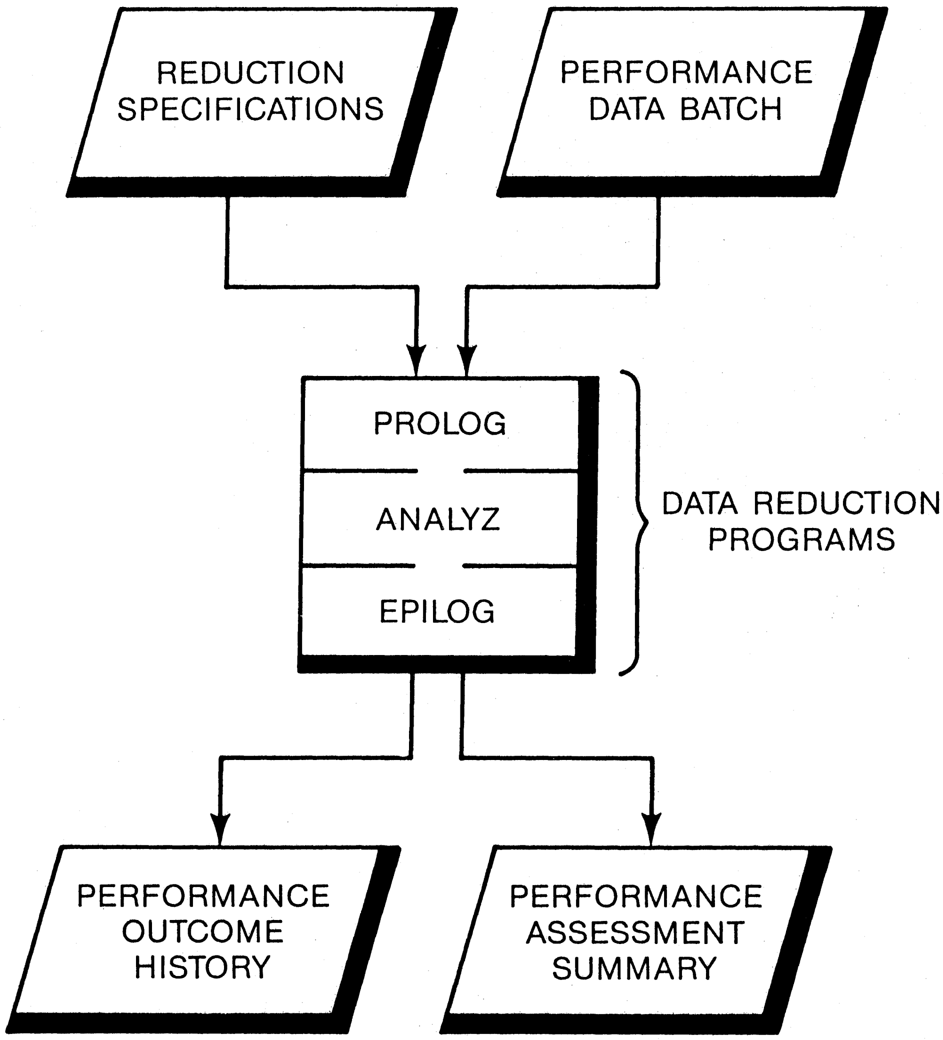


Figure 13. Outline of the data reduction process.

If no errors were detected, PROLOG combined overhead reference events observed at the source and destination interfaces into a unified event history. If an error was observed, a diagnostic was issued and processing was terminated.

In the second phase of the reduction process, ANALYZ examined reference event records in the overhead and user information transfer event histories to identify individual performance trials and classify their outcomes. Performance assessment procedures for the access, user information transfer, and disengagement functions were carried out by subroutines ACCESS, TRANSF, and DISENG, respectively. In access and disengagement performance assessment, ACCESS and DISENG identified the start and end of a performance trial by observing particular communication state transitions recorded in the consolidated event history. In user information transfer performance assessment, a data correlation routine first compared source and destination user information to identify successive bit transfer attempts and partition these into a sequence of block transfer attempts. Results of the comparison were written to a correlator output file that was subsequently processed by TRANSF to classify outcomes of bit and block transfer attempts and to select and analyze a sequence of transfer samples for the measurement of Transfer Denial Probability.

Assessment routines produced a performance outcome file for each primary delay parameter measured in a test. The outcome record for a successful trial contained both overall and user performance times, whereas the record for an unsuccessful trial contained a code that specified the particular failure outcome. An example of an access outcome file is shown in Figure 14. Outcome files served as input to the data analysis process.

In the final phase of the reduction process, EPILOG produced a user-oriented performance assessment summary for the test. This summary listed test descriptors, the specified parameter values used in outcome determination, the observed outcome counts, and the measured parameter values. An example of a performance assessment summary is shown in Figure 15.

Data reduction procedures were partitioned into three main programs (instead of being combined in one main program with three primary subroutines) in order to reduce the required computer memory. A single program and the associated subroutines would have contained about 4000 FORTRAN instructions and would have been too large to be directly executable on some smaller computer systems (including the one used by ITS to develop the reduction software).

```
ACCESS OUTCOME
ITS PDN ACCESS/DISENGAGEMENT PERFORMANCE MEASUREMENT     0986.001    1
NTIA - PDN test from Washington,                         0986
          44.397          3.622
          41.875          1.395
             -2.             -2.
          40.422          1.397
          41.999          1.394
          40.743          1.409
          41.579          1.410
          40.607          1.394
          40.611          1.397
          40.569          1.395
          40.822          1.400
          42.208          1.395
          40.771          1.396
          40.765          1.395
          42.886          1.398
          41.894          1.395
          40.817          1.399
          43.550          1.396
          41.879          1.601
          42.374          1.395
            -30.            -30.
```

NONNEGATIVE VALUES IN COLUMNS 1 AND 2 DENOTE MEASURED VALUES (IN SECONDS) OF TOTAL PERFORMANCE TIME AND USER PERFORMANCE TIME, RESPECTIVELY, FOR INDIVIDUAL SUCCESSFUL ACCESS ATTEMPTS.

NEGATIVE ENTRIES INDICATE OUTCOMES OF UNSUCCESSFUL OR INCOMPLETE ACCESS ATTEMPTS ACCORDING TO THE FOLLOWING CODE(S):

-2 = ACCESS DENIAL

END OF OUTCOME DATA IS INDICATED BY -30.

Figure 14. Access outcome file for an access-disengagement test.

4.2.3 Data Analysis for Individual Tests

The data analysis process for an individual test produced estimated performance parameter values and their 90% and 95% confidence limits based on the test. For access-disengagement tests, estimates were produced for all access and disengagement parameters defined in ANS X3.102. For user information transfer tests, estimates were produced for all ANS X3.102 bit and block transfer parameters and for Transfer Denial Probability. Because there was only one throughput trial in a test, it was not possible to obtain confidence limits for User Information Bit Transfer Rate and User Fraction of Input/Output Time. As discussed previously, misdelivery parameters were not measured.

Parameter estimates and their confidence limits were calculated by STAT, a comprehensive statistical design and analysis FORTRAN computer program (Miles, 1984). In a delay analysis, execution of the STAT program produced estimates and their 90% or 95% confidence limits for a single primary delay parameter (e.g., Access Time) and the associated ancillary parameter (e.g., User Fraction of Access Time). In a failure analysis, execution of STAT produced an estimate and its 90% or 95% confidence limits for a single failure probability parameter (e.g., Access Denial). STAT was written as an interactive program in which certain data are entered from a keyboard in response to program prompts. The software that performed post-test processing utilized I/O redirection to enter keyboard responses from a prompt file prepared prior to invoking the STAT program.

Delay analyses for an access-disengagement test were implemented by MKTIMES, a shell script included in the comprehensive post-test processing software discussed earlier. For each primary access and disengagement delay parameter, MKTIMES first generated a performance data file for input to the STAT program, then called STAT to calculate estimates and their confidence limits for the primary parameter and its ancillary associate. The input data file contained the overall and user performance times for each successful trial of the relevant function, and was obtained by editing the corresponding performance outcome file produced during the reduction process. Two STAT calls were required for each primary parameter--the first calculated estimates for the 90% confidence level and the second calculated estimates for the 95% level. In each call to STAT, keyboard responses were input from an appropriate prompt

```
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*                                                                             *
*                                                                             *
*                     PERFORMANCE ASSESSMENT  SUMMARY                         *
*                                                                             *
*                                                                             *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *


* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*                                                                             *
*                                                                             *
*                        PERFORMANCE MEASUREMENT                              *
*                                                                             *
*    -----------------------------------------------------------------        *
*    ITS PDN ACCESS/DISENGAGEMENT PERFORMANCE MEASUREMENT     0986.001        *
*    -----------------------------------------------------------------        *
*                                                                             *
*                                                                             *
*    REDUCTION RUN . . . . . . . . . . . . . . . . . . . . . . .    1         *
*                                                                             *
*                                                                             *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *


* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*                                                                             *
*                                                                             *
*                        PERFORMANCE DATA  BATCH                              *
*                                                                             *
*      -------------------------------------------------------------          *
*      NTIA - PDN test from Washington,                         0986          *
*      -------------------------------------------------------------          *
*                                                                             *
*                                                                             *
*    SOURCE USER  . . . . . . . . . . . . . . NTIA - Term2 (NBS-Gaithers      *
*                                                                             *
*    DESTINATION USER . . . . . . . . . . . . NTIA - Host1 (Boulder)          *
*                                                                             *
*    ORIGINATING USER . . . . . . . . . . . . . . . . . . . . . . SOURCE      *
*                                                                             *
*                                                                             *
*    SESSION TYPE . . . . . . . . . . . . . . . . . . CONNECTION ORIENTED     *
*                                                                             *
*    INITIAL DISENGAGEMENT TYPE . . . . . . . . . . . . . . . . NEGOTIATED    *
*                                                                             *
*                                                                             *
*    MEASUREMENT START TIME . . . . . . . . .  12/15/83  04:00:35.329 UT      *
*                                                                             *
*    MEASUREMENT END TIME . . . . . . . . . .  12/15/83  04:38:06.519 UT      *
*                                                                             *
*                                                                             *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
```

Figure 15 (Part 1). Performance assessment summary for an access-disengagement test.

```
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
ITS PDN ACCESS/DISENGAGEMENT PERFORMANCE MEASUREMENT    0986.001     RUN    1
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -


* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*                                                                           *
*                       ACCESS ASSESSMENT SUMMARY                           *
*                  FOR CURRENT  PERFORMANCE DATA BATCH                      *
*                                                                           *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*                                                                           *
*                         ACCESS SPECIFICATIONS                             *
*                                                                           *
*                                 -----                                     *
*                                                                           *
*  SPECIFIED ACCESS TIME . . . . . . . . . . . . . . . . .   45.000 SECONDS *
*  SPECIFIED USER FRACTION OF ACCESS TIME  . . . . . . . .   0.0100         *
*                                                                           *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*                                                                           *
*                     ACCESS PERFORMANCE STATISTICS                         *
*                                                                           *
*                                 -----                                     *
*                                                                           *
*  NUMBER OF ACCESS ATTEMPTS . . . . . . . . . . . . . . . . .   20 (+)     *
*  NUMBER OF 'SUCCESSFUL ACCESS' OUTCOMES  . . . . . . . . . .   19         *
*  NUMBER OF 'INCORRECT ACCESS' OUTCOMES . . . . . . . . . . .    0         *
*  NUMBER OF 'ACCESS DENIAL' OUTCOMES  . . . . . . . . . . . .    1         *
*  NUMBER OF 'ACCESS OUTAGE' OUTCOMES  . . . . . . . . . . . .    0         *
*                                                                           *
*  (+) THIS NUMBER EXCLUDES ACCESS ATTEMPTS                                 *
*      THAT FAIL DUE TO USER BLOCKING                                       *
*                                                                           *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*                                                                           *
*              MEASURED VALUES OF  ACCESS PERFORMANCE PARAMETERS            *
*                                                                           *
*                                 -----                                     *
*                                                                           *
*  ACCESS TIME . . . . . . . . . . . . . . . . . . . . . .   41.619 SECONDS *
*  USER FRACTION OF ACCESS TIME  . . . . . . . . . . . . .   0.0367         *
*                                                                           *
*  INCORRECT ACCESS PROBABILITY  . . . . . . . . . . .            0         *
*  ACCESS DENIAL PROBABILITY . . . . . . . . . . . . . . 5.0 X 10(-02)      *
*  ACCESS OUTAGE PROBABILITY . . . . . . . . . . . . .            0         *
*                                                                           *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
```

Figure 15 (Part 2). Performance assessment summary for an access-disengagement test.

```
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*                                                                             *
*                    DISENGAGEMENT  ASSESSMENT SUMMARY                        *
*                   FOR  CURRENT PERFORMANCE DATA BATCH                       *
*                                                                             *
*                    (SOURCE DISENGAGEMENT ATTEMPTS)                          *
*                                                                             *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*                                                                             *
*                    DISENGAGEMENT  SPECIFICATIONS                            *
*                                                                             *
*                               -----                                         *
*                                                                             *
*  SPECIFIED DISENGAGEMENT TIME . . . . . . . . . . . .    15.000 SECONDS     *
*  SPECIFIED USER FRACTION OF DISENGAGEMENT TIME . . . .   0.1000             *
*                                                                             *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*                                                                             *
*                 DISENGAGEMENT  PERFORMANCE STATISTICS                       *
*                                                                             *
*                               -----                                         *
*                                                                             *
*  NUMBER OF DISENGAGEMENT ATTEMPTS . . . . . . . . . . . .    19 (+)         *
*  NUMBER OF 'SUCCESSFUL DISENGAGEMENT' OUTCOMES . . . . . .   19             *
*  NUMBER OF 'DISENGAGEMENT DENIAL' OUTCOMES . . . . . . . .    0             *
*                                                                             *
*  (+) THIS NUMBER EXCLUDES DISENGAGEMENT ATTEMPTS                            *
*      THAT FAIL DUE TO USER DISENGAGEMENT BLOCKING                           *
*                                                                             *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*                                                                             *
*         MEASURED VALUES OF DISENGAGEMENT PERFORMANCE PARAMETERS             *
*                                                                             *
*                               -----                                         *
*                                                                             *
*  DISENGAGEMENT TIME . . . . . . . . . . . . . . . . . .  13.196 SECONDS     *
*  USER FRACTION OF DISENGAGEMENT TIME . . . . . . . . . . 0.0724             *
*                                                                             *
*  DISENGAGEMENT DENIAL PROBABILITY . . . . . . . .             0             *
*                                                                             *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
```

Figure 15 (Part 3). Performance assessment summary for an access-disengagement test.

```
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
ITS PDN ACCESS/DISENGAGEMENT PERFORMANCE MEASUREMENT    0986.001     RUN    1
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -


* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*                                                                             *
*                    DISENGAGEMENT  ASSESSMENT SUMMARY                        *
*                   FOR  CURRENT PERFORMANCE DATA BATCH                       *
*                                                                             *
*                  (DESTINATION  DISENGAGEMENT ATTEMPTS)                      *
*                                                                             *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*                                                                             *
*                      DISENGAGEMENT  SPECIFICATIONS                          *
*                                                                             *
*                                -----                                        *
*                                                                             *
*  SPECIFIED DISENGAGEMENT TIME . . . . . . . . . . . .     5.000 SECONDS     *
*  SPECIFIED USER FRACTION OF DISENGAGEMENT TIME . . . .   0.1000             *
*                                                                             *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*                                                                             *
*                 DISENGAGEMENT  PERFORMANCE STATISTICS                       *
*                                                                             *
*                                -----                                        *
*                                                                             *
*  NUMBER OF DISENGAGEMENT ATTEMPTS . . . . . . . . . . . .     19 (+)        *
*  NUMBER OF 'SUCCESSFUL DISENGAGEMENT' OUTCOMES . . . . . .    19            *
*  NUMBER OF 'DISENGAGEMENT DENIAL' OUTCOMES . . . . . . . .     0            *
*                                                                             *
*  (+) THIS NUMBER EXCLUDES DISENGAGEMENT ATTEMPTS                            *
*      THAT FAIL DUE TO USER DISENGAGEMENT BLOCKING                           *
*                                                                             *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*                                                                             *
*          MEASURED VALUES OF DISENGAGEMENT PERFORMANCE PARAMETERS            *
*                                                                             *
*                                -----                                        *
*                                                                             *
*  DISENGAGEMENT TIME . . . . . . . . . . . . . . . . . .   3.062 SECONDS     *
*  USER FRACTION OF DISENGAGEMENT TIME . . . . . . . . . .  0.2252            *
*                                                                             *
*  DISENGAGEMENT DENIAL PROBABILITY . . . . . . . .             0             *
*                                                                             *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
```

Figure 15 (Part 4). Performance assessment summary for an access-disengagement test.

file and output was redirected to a temporary file. (Because keyboard responses in a delay analysis were independent of the performance data when these data were input to STAT from a file, the prompt files were prepared off-line prior to the start of post-test processing.) When all parameter estimates had been calculated, MKTIMES called a C program (TABLE) that produced a concise summary of delay measurement results. An example of a measurement results summary for access and disengagement delays is shown in Figure 16a.

Failure analyses for an access-disengagement test were implemented by MKFAIL, another shell script in the post-test processing software. MKFAIL first called a subordinate shell script (MKPRMT) to generate prompt files for STAT. A separate prompt file was generated for each access and disengagement failure probability parameter and each confidence level. A prompt file for a given parameter included the number of trials, the number of failures, and the number of pairs of consecutive failures. These values were extracted from the performance assessment summary file and the relevant performance outcome file produced during the reduction process. After all prompt files had been generated, MKFAIL called the STAT program to calculate estimates and their 90% and 95% confidence limits for each failure probability parameter. In each call to STAT, keyboard responses were input from the appropriate prompt file and output was redirected to a temporary file. MKFAIL concluded by calling a C program (TABLEF) to produce a summary of failure probability measurement results similar to that output by MKTIMES for delay parameters. An example of a measurement results summary for access and disengagement failures is shown in Figure 16b.

Delay and failure analyses for a user information transfer test were implemented by MKXTIMES and MKXFAIL, a pair of shell scripts analogous to MKTIMES and MKFAIL. MKXFAIL did not include procedures for counting pairs of consecutive bit transfer failures. If the reduction routines observed one or more instances of a particular bit transfer failure, MKXFAIL suppressed estimation of the corresponding failure probability and its confidence limits. After the completion of such a post-test processing run, the operator obtained the number of pairs of consecutive failures by examining the correlator output file. The relevant failure probability estimate and its confidence limits were then calculated by interactively running the STAT program from an operator terminal. Finally, these estimates were entered in the measurement results summary with a text editor.

MEASUREMENT RESULTS SUMMARY

RUN: ITS PDN ACCESS/DISENGAGEMENT PERFORMANCE MEASUREMENT 0986.001
BATCH: NTIA - PDN test from Washington, 0986

PERFORMANCE PARAMETER	SAMPLE SIZE	ESTIMATED VALUE	CONFIDENCE LEVEL (PERCENT)	LOWER CONFIDENCE LIMIT	UPPER CONFIDENCE LIMIT
ACCESS TIME	19	.41619e+02	90	.41164e+02	.42074e+02
			95	.41068e+02	.42171e+02
USER FRACTION OF ACCESS TIME	19	.36661e-01	90	.32306e-01	.41016e-01
			95	.31472e-01	.41850e-01
			95	.70380e+01	.75216e+01
DISENGAGEMENT TIME (SOURCE)	19	.13196e+02	90	.13022e+02	.13371e+02
			95	.12985e+02	.13408e+02
USER FRACTION OF DISENGAGEMENT TIME (SOURCE)	19	.72411e-01	90	.65257e-01	.79566e-01
			95	.63886e-01	.80936e-01
DISENGAGEMENT TIME (DESTINATION)	19	.30620e+01	90	.28843e+01	.32397e+01
			95	.28467e+01	.32773e+01
USER FRACTION OF DISENGAGEMENT TIME (DESTINATION)	19	.22516e+00	90	.19857e+00	.25175e+00
			95	.19348e+00	.25684e+00

ESTIMATED PERFORMANCE TIMES ARE EXPRESSED IN SECONDS

a. Measurement Results Summary for Delays

MEASUREMENT RESULTS SUMMARY

RUN: ITS PDN ACCESS/DISENGAGEMENT PERFORMANCE MEASUREMENT 0986.001
BATCH: NTIA - PDN test from Washington, 0986

PERFORMANCE PARAMETER	SAMPLE SIZE	ESTIMATED VALUE	CONFIDENCE LEVEL (PERCENT)	LOWER CONFIDENCE LIMIT	UPPER CONFIDENCE LIMIT
INCORRECT ACCESS PROBABILITY	20	.00000e+00	90	.00000e+00	.10785e+00
			95	.00000e+00	.13409e+00
ACCESS DENIAL PROBABILITY	20	.50000e-01	90	.00000e+00	.19817e+00
			95	.00000e+00	.23110e+00
ACCESS OUTAGE PROBABILITY	20	.00000e+00	90	.00000e+00	.10785e+00
			95	.00000e+00	.13409e+00
DISENGAGEMENT DENIAL PROBABILITY (SOURCE)	19	.00000e+00	90	.00000e+00	.11262e+00
			95	.00000e+00	.13975e+00
DISENGAGEMENT DENIAL PROBABILITY (DESTINATION)	19	.00000e+00	90	.00000e+00	.11262e+00
			95	.00000e+00	.13975e+00

WHEN THE OBSERVED NUMBER OF FAILURES IS 0 OR 1, THE CONDITIONAL PROBABILITY OF FAILURE USED TO ESTIMATE CONFIDENCE LIMITS IS 0.3 FOR ACCESS DENIAL PROBABILITY AND 0.1 FOR ALL OTHER PERFORMANCE PARAMETERS

b. Measurement Results Summary for Failures

Figure 16. Measurement results summaries for an access-disengagement test.

Analyses performed by the STAT program accounted for possible sequential dependence by treating the successive trials in a test as a stationary first-order Markov process. In the Markov model, the outcome of a trial (an observed delay or the occurrence/nonoccurrence of a particular failure) may be influenced by the immediately preceding outcome, but not by any outcome earlier than that. The usual effect of such dependence is to increase the length of a confidence interval beyond that calculated on the basis of independent trials. If, in fact, there is no dependence, the interval derived from the Markov model reduces to the classical interval based on independence. In delay analyses, the Markov model was implemented by the autocorrelation of lag 1; in failure analyses, the model was implemented by the conditional probability of a failure given that the preceding outcome was a failure. When a test resulted in two or more failures, STAT estimated that probability from the number of trials, failures, and pairs of consecutive failures. When the number of failures is zero or one (so the number of pairs of consecutive failures is zero), STAT used an operator-specified value for the conditional probability. Additional information is provided in a report by Miles (1984), which discusses statistical concepts underlying the STAT program, describes the operation of the program, and summarizes computational formulas.

4.3 Multitest Data Analysis

In the final phase of the performance measurements conducted by ITS, two types of multitest data analyses were carried out for selected groups of tests. First, several Latin squares of the kind described in Section 3.5 were examined for the significance of any differences among days and among time periods. This study, which used standard methods for the analysis of variance, is described in Appendix H.

In the second type of multitest analysis, performance parameter estimates and their 95% confidence limits based on pooled data were obtained for each of several groups of tests. In this study, access-disengagement tests that used DTMF (tone) dialing were divided into five groups according to the network connection. Medium-block (128-character) user information transfer tests in which high utilization and flow control were implemented were similarly grouped. Each group of tests thus represented one or more source cities (remote terminal sites) and various days and time periods.

The estimation of parameter values and their confidence limits for pooled data was based on a linear model for the analysis of variance. This model assumed that there are three additive components of variation: among levels of a given factor (the source city in this study), among tests within a factor level, and among trials within a test. The model also assumed that factor levels have been chosen at random from a set of all possible levels, the tests actually performed for a given level are a random sample of all possible tests for that level, and dependence among trials in a given test is described by a first-order Markov process. Appendix H presents the theory underlying the analysis and derives formulas for the estimation of parameter values and their confidence limits. It also includes some illustrative estimates for both delay and failure probability parameters from the ITS measurements.

Parameter estimates and their confidence limits for multitest groups were evaluated by STAR, a revised and enhanced version of program STAT discussed in Section 4.2.3. As in the case of the STAT program, execution of STAR in a delay analysis produced estimates and their 90% or 95% confidence limits for a single primary delay parameter and the associated ancillary parameter. In a rate analysis, STAR produced estimates for both the rate parameter (User Information Bit Transfer Rate) and the associated performance time (input/output time). In a failure analysis, STAR produced estimates for a single failure probability parameter. Like its predecessor, STAR was written as an interactive FORTRAN program.

For a given group of tests and a specified parameter, STAR calculated estimates and their 95% confidence limits using each of three pooling procedures: pooling all trials from the tests, pooling all test means, and pooling all source city (factor level) means. These pooling procedures generally produced different results; the appropriate choice of results is summarized by the flow chart in Figure 17.

To determine if there were statistically significant differences among test means (at the 5% significance level), STAR examined the hypothesis that all test means are equal. The program calculated a statistic that

- o depended on the dispersion of test means about the mean of all trials, and
- o had a known distribution under the assumptions of the model.

STAR then evaluated the 5% point of the statistic's distribution. The hypothesis was accepted if the calculated value of the statistic was less than

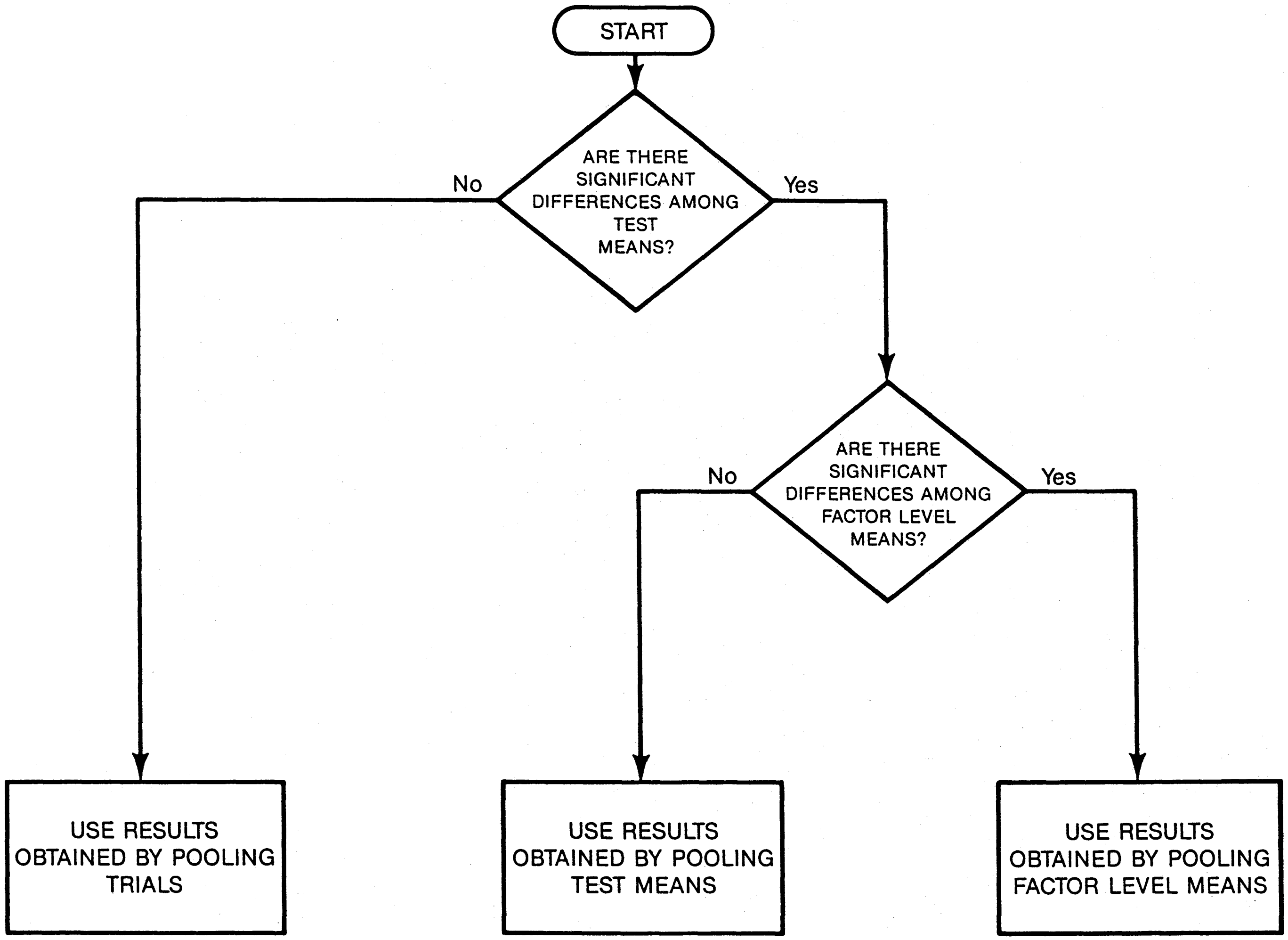


Figure 17. Acceptable pooling procedures for analysis of multiple tests.

the 5% point of the associated distribution, and was rejected otherwise. Determining if there were significant differences among factor level means was carried out in an analogous manner. In this case, STAR calculated a statistic that depended on the dispersion of factor level means about the mean of all test means. Both the calculated value of the relevant statistic and the 5% point of the associated distribution were included in the printed output produced by STAR.

The acceptability of pooling in the analysis for a delay parameter was determined only by observed values of overall performance times; it did not depend on user performance times or fractions. In the analysis for a rate parameter, the acceptability of pooling was determined only by observed values of overall input/output performance times; it did not depend on transfer rates or user performance times or fractions. In the analysis for a failure probability parameter, the acceptability of pooling was jointly determined by observed values of failure probabilities and conditional failure probabilities.

Delay, rate, and failure analyses for multiple tests were implemented by the shell scripts DELAY, RATE, and FAIL, respectively. Given a parameter and a specified set of tests, each of these shell scripts

- generated a prompt file containing the keyboard responses to prompts issued by the STAR program,
- called a subordinate shell script to calculate relevant sample means and standard deviations for individual tests in the specified set,
- called STAR to carry out the analysis for the 95% confidence level as outlined previously, and
- generated a concise summary of results and wrote these to a file.

Input to a shell script consisted of

- a file (LOG.WRK) that specified the tests to be analyzed,
- a pair of arguments that respectively specified a particular parameter and a particular performance factor, and
- one or more files that contained the relevant performance data.

The first step in the analysis of a group of tests was the generation of the LOG.WRK file for the group. Each record in this file corresponded to a selected test and was extracted from a master file of access-disengagement tests (listed in Table 9) or a master file of user information transfer tests (listed in Table 14) by using the UNIX™ GREP utility.

Performance data for delay analyses were contained in edited versions of the performance outcome files produced in the data reduction process and described in Section 4.2.2. Performance data for rate analyses were contained in a set of files, where each file contained a throughput data record for a single test. This record consisted of the overall and user input/output performance times for a throughput sample, and the number of successfully transferred user information bits in the sample. Performance data for failure analyses were contained in a set of six failure summary files, where each file corresponded to a particular function as follows:

ACFAIL - access failures
B1FAIL - bit transfer failures
B2FAIL - block transfer failures
B3FAIL - transfer sample failures
D1FAIL - source disengagement failures
D2FAIL - destination disengagement failures

A file for a particular function contained a separate failure summary record for each test. Each failure summary record included (in addition to the test number) the number of trials in the test and both the number of failures and the number of pairs of consecutive failures for each failure outcome type associated with the function.

The prompt file for the analysis of a specified delay parameter contained the name of the relevant performance data file for each test in the selected group. A similar prompt file was generated for a rate analysis. The prompt file for the analysis of a specified failure probability parameter contained, for each test in the group, a record that listed the relevant performance data: the number of trials, the number of failures, and the number of pairs of consecutive failures. These data were extracted by the FAIL shell script from the appropriate failure summary file described above.

Each execution of a DELAY, RATE, or FAIL shell script concluded by producing a concise summary of results. A summary for the analysis of a delay parameter (Access Time) is shown in Figure 18. Note that the summary indicates the statistical acceptability of pooling trials and test means, as outlined earlier in this section.

ANALYSIS OF MULTIPLE TESTS

Analysis Using delay 21 Files
Fri Jun 17 12:07:01 MDT 1988

11 Test Files Used with Variable Condition 1

Test #		#	Times Mean	Times Std Dev	User Fractions Mean	User Fractions Std Dev
775	ftw A fri 1 L foff tone	20	38.291	1.608	0.0397	0.0199
823	sea A fri 2 L foff tone	20	42.439	1.527	0.0339	0.0047
815	sea A fri 6 L foff tone	20	41.576	1.269	0.0352	0.0044
835	sea A mon 3 L foff tone	15	42.954	1.325	0.0345	0.0053
858	sea A thu 1 L foff tone	20	42.284	1.338	0.0345	0.0053
876	sea A thu 4 L foff tone	20	42.313	2.197	0.0350	0.0064
811	sea A thu 5 L foff tone	19	41.163	1.015	0.0373	0.0065
997	wdc A thu 3 L f-on tone	17	41.751	2.198	0.0356	0.0075
928	wdc A tue 1 L foff tone	20	44.500	4.380	0.0332	0.0068
952	wdc A tue 5 L f-on tone	20	39.813	1.625	0.0368	0.0043
978	wdc A wed 4 L f-on tone	18	42.304	1.820	0.0351	0.0054

-----------------------------Calculated Results------------------------------

TIMES (W) AND FRACTION OF TIMES (V)

NUMBER OF LEVELS = 3
NUMBER OF TESTS = 11
NUMBER OF TRIALS = 209

WEIGHTED AVERAGE AUTOCORRELATION COEFFICIENT
OF LAG 1 OVER THE 11 TESTS = .3927E+00 #
AVERAGE AUTOCORRELATION COEFFICIENT
OF LAG 1 FOR THE 209 POOLED TRIALS = .4998E+00 @

	EFFECTIVE DEGREES OF FREEDOM		F STAT.	F DIST. (5%)		95% LOWER CONFIDENCE LIMIT	ESTIMATE OF THE MEAN	95% UPPER CONFIDENCE LIMIT	
AMONG TRIALS	80	10	.4961E+01	.1963E+01	W	.4112E+02	.4173E+02	.4234E+02	
	-	-	-	-	V	.3423E-01	.3547E-01	.3671E-01	
AMONG TESTS	8	2	.4011E+01	.4460E+01	W	.4067E+02	.4176E+02	.4286E+02	*
	-	-	-	-	V	.3416E-01	.3551E-01	.3686E-01	
AMONG LEVELS	-	-	-	-	W	.3536E+02	.4083E+02	.4631E+02	
	-	-	-	-	V	.2935E-01	.3676E-01	.4417E-01	

USED TO DETERMINE THE EFFECTIVE DEGREES OF FREEDOM FOR THE FTEST.
@ USED TO DETERMINE THE EFFECTIVE DEGREES OF FREEDOM FOR THE CONFIDENCE LIMITS.
* AT RIGHT OF UPPER CONFIDENCE LIMIT INDICATES THIS POOLING
IS ACCEPTABLE AT THE 5% LEVEL.

Figure 18. Measurement results summary for a multitest delay analysis.

5. MEASUREMENT RESULTS

The second objective of the ITS performance measurement program was to demonstrate the applicability of the new measurement system by obtaining some values that characterize the end-to-end performance of connections established over three public data networks, the public switched telephone network, and the Federal Telecommunications System. This section describes measurement program results related to that objective. The results are based on 51 access-disengagement tests and 214 user information transfer tests conducted during October - December 1983. The description consists of four subsections. The first contains a concise summary of performance parameter estimates obtained by combining data from selected groups of tests. The second and third subsections present more detailed descriptions of results from access-disengagement tests and user information transfer tests, respectively. The last subsection describes some of the measurement problems encountered during the experiment and outlines their solutions.

The results presented in this section represent the validation of the measurement system. The presentation makes frequent use of four types of graphical displays: box plots, histograms, chronological plots, and linear regression plots. An example of each type of plot is illustrated in Figure 19. A box plot summarizes a sample distribution in terms of five percentiles: the 25th and 75th percentiles of a sample are shown as the ends of a rectangle (i.e., a "box"), the median (50th percentile) is shown as a line segment across the box, and the smallest and largest observations are shown as the ends of line segments extending vertically from the box. The smallest and largest observations correspond approximately to the 50/n and 100-50/n percentiles, respectively, for sample size n. Both box plots and the more familiar histograms are effective in displaying asymmetry of a distribution, but neither type of plot reveals autocorrelation that may exist. Chronological plots, in which observed values are plotted as a function of trial number, are useful in displaying relationships (e.g., autocorrelation) among successive trials. Linear regression plots determined by the method of least squares are used in several instances to represent the dependence of Block Transfer Time on block size.

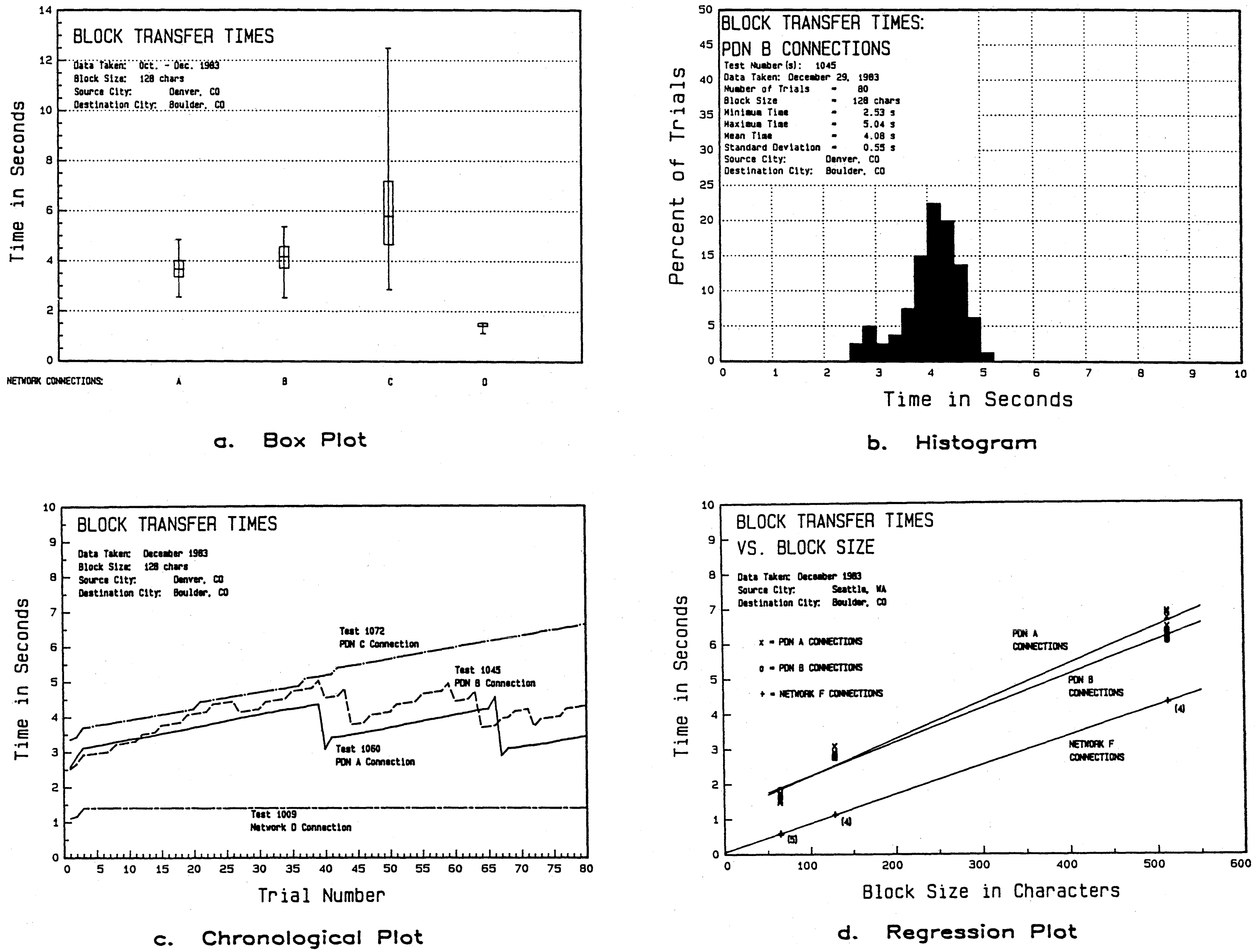


Figure 19. Types of plots used to present measurement results.

5.1 Performance Parameter Summaries

This section includes a set of tables (Tables 4-8) concisely summarizing parameter estimates and their 95% confidence limits that characterize, under specified conditions, the end-to-end data communication performance observed on connections over each of the switched networks utilized in the ITS tests. The values in these tables were obtained by pooling results from selected tests in the manner outlined in Section 4.3 and described in greater detail in Appendix H. The calculated parameter estimates and their confidence limits account for variations among source cities and among tests, as well as variations among trials within a test.

An upper confidence limit for failure probabilities was determined even if no failures were observed. To do this, the conditional probability of a failure given that a failure occurred on the previous trial must be known or assumed. For these tables, the possibly conservative value of 0.8 was assumed. (This value provides a larger upper confidence limit than would a smaller value.) Of course, the lower confidence limit is zero when no failures are observed.

In the tables there are four columns to the right of the upper confidence limit column. In the "pooling disposition" column, "1" indicates that all trial values in the selected tests could be pooled, "2" indicates that test means (but not individual trial values) could be pooled, and "3" indicates that the means for source cities were used (i.e., test means could not be pooled regardless of city). The numbers in the "number of cities" column are the number of source cities over which pooling occurred. The next column lists the number of tests, and the last column lists the number of trials.

Following is a brief synopsis of the tables for each performance parameter, listed according to function.

5.1.1 Access Parameters

Access parameter estimates presented in the summary tables are based on access-disengagement tests in which tone (DTMF) dialing was used.

- o Access Time. About 35 seconds were required to establish access in connections over network D, and about 40-45 seconds were required in connections over other networks.

- o User Fraction of Access Time. This fraction was generally 0.032-0.042, with connections over network D having the largest fraction (and the shortest Access Time).

Table 4. Summary of Performance Parameter Estimates for PDN A Connections

Performance Parameter Summary For PDN A Connections

Performance Parameter	*95% Lower Limit*	*Mean Estimate*	*95% Upper Limit*	*Pooling Disposition***	*Number of Cities*	*Number of Tests*	*Number of Trials*
Access Time (s)	40.7	41.8	42.9	2	3	11	209
User Fraction of Access Time	0.034	0.036	0.037	2	3	11	209
Incorrect Access Probability	0	0	0.062*	1	3	11	220
Access Outage Probability	0	0	0.062*	1	3	11	220
Access Denial Probability	0.018	0.050	0.107	1	3	11	220
Block Transfer Time (s)	3.61	3.79	3.97	2	2	7	559
User Fraction of Block Transfer Time	0.077	0.089	0.102	2	2	7	559
User Fraction of Input/Output Time	0.110	0.214	0.317	3	2	7	7
User Information Bit Transfer Rate (bps)	421	814	1207	3	2	7	7
Bit Error Probability	6.0×10^{-7}	7.0×10^{-6}	3.0×10^{-5}	1	2	7	573440
Bit Misdelivery Probability	-	-	-	-	-	-	-
Extra Bit Probability	0	0	3.0×10^{-5}*	1	2	7	573440
Bit Loss Probability	0	0	3.0×10^{-5}*	1	2	7	573440
Block Error Probability	0	2.0×10^{-3}	3.0×10^{-2}	1	2	7	560
Block Misdelivery Probability	-	-	-	-	-	-	-
Extra Block Probability	0	0	3.0×10^{-2}*	1	2	7	560
Block Loss Probability	0	0	3.0×10^{-2}*	1	2	7	560
Transfer Denial Probability	0	0	5.0×10^{-2}*	1	2	7	273
Source Disengagement Time (s)	14.3	15.1	15.8	2	3	11	194
User Fraction of Source Disengagement Time	0.058	0.061	0.065	2	3	11	194
Source Disengagement Denial Probability	0.042	0.072	0.116	1	3	11	209
Destination Disengagement Time (s)	4.9	5.2	5.4	1	3	11	207
User Fraction of Destination Disengagement Time	0.121	0.128	0.134	1	3	11	207
Destination Disengagement Denial Probability	0.008	0.018	0.033	2	3	11	209

* Conditional probability assumed to be 0.8
\- Not measured

** 1 means no significant difference among tests or cities, so all trials pooled.
2 means no significant difference among cities, so all test means pooled.
3 means significant difference among cities, so no pooling; only 1 or 2 degrees of freedom for confidence limit.

Table 5. Summary of Performance Parameter Estimates for PDN B Connections

Performance Parameter Summary For PDN B Connections

Performance Parameter	*95% Lower Limit*	*Mean Estimate*	*95% Upper Limit*	*Pooling Disposition***	*Number of Cities*	*Number of Tests*	*Number of Trials*
Access Time (s)	41.5	42.4	43.4	2	3	12	212
User Fraction of Access Time	0.034	0.035	0.036	2	3	12	212
Incorrect Access Probability	0	0	0.058*	1	3	12	240
Access Outage Probability	0.025	0.046	0.080	1	3	12	240
Access Denial Probability	0.041	0.071	0.114	1	3	12	240
Block Transfer Time (s)	3.74	4.37	4.99	2	2	7	560
User Fraction of Block Transfer Time	0.092	0.098	0.103	2	2	7	560
User Fraction of Input/Output time	0.217	0.227	0.237	1	2	7	7
User Information Bit Transfer Rate (bps)	826	865	9031	2	7	7	
Bit Error Probability	0	0	$3.0x10^{-5}$*	1	2	7	573440
Bit Misdelivery Probability	-	-	-	-	-	-	-
Extra Bit Probability	0	0	$3.0x10^{-5}$*	1	2	7	573440
Bit Loss Probability	0	0	$3.0x10^{-5}$*	1	2	7	573440
Block Error Probability	0	0	$3.0x10^{-2}$*	1	2	7	560
Block Misdelivery Probability	-	-	$3.0x10^{-2}$*	1	2	7	560
Extra Block Probability	0	0	$3.0x10^{-2}$*	1	2	7	560
Block Loss Probability	0	0	$3.0x10^{-2}$*	1	2	7	560
Transfer Denial Probability	0	0	$5.0x10^{-2}$*	1	2	7	273
Source Disengagement Time (s)	11.7	12.8	13.9	3	3	12	194
User Fraction of Source Disengagement Time	0.061	0.070	0.078	3	3	12	194
Source Disengagement Denial Probability	0.053	0.085	0.130	1	3	12	212
Destination Disengagement Time (s)	1.7	2.5	3.4	3	3	12	212
User Fraction of Destination Disengagement Time	0.147	0.251	0.355	3	3	12	212
Destination Disengagement Denial Probability	0	0	0.06*	1	3	12	212

* Conditional probability assumed to be 0.8
- Not measured

** 1 means no significant difference among tests or cities, so all trials pooled.
2 means no significant difference among cities, so all test means pooled.
3 means significant difference among cities, so no pooling; only 1 or 2 degrees of freedom for confidence limit.

Table 6. Summary of Performance Parameter Estimates for PDN C Connections

Performance Parameter Summary For PDN C Connections

Performance Parameter	*95% Lower Limit*	*Mean Estimate*	*95% Upper Limit*	*Pooling Disposition***	*Number of Cities*	*Number of Tests*	*Number of Trials*
Access Time (s)	44.2	44.7	45.1	1	2	7	111
User Fraction of Access Time	0.032	0.034	0.036	1	2	7	111
Incorrect Access Probability	0	0	0.094*	1	2	7	140
Access Outage Probability	0	0	0.094*	1	2	7	140
Access Denial Probability	0.056	0.192	0.383	2	2	7	140
Block Transfer Time (s)	4.08	5.86	7.63	1	2	7	560
User Fraction of Block Transfer Time	0.075	0.105	0.134	1	2	7	560
User Fraction of Input/Output Time	0.230	0.238	0.243	1	2	7	7
User Information Bit Transfer Rate (bps)	887	906	926	1	2	7	7
Bit Error Probability	0	0	3.0x10^{-5}*	1	2	7	573440
Bit Misdelivery Probability	-	-	-	-	-	-	-
Extra Bit Probability	0	0	3.0x10^{-5}*	1	2	7	573440
Bit Loss Probability	0	0	3.0x10^{-5}*	1	2	7	573440
Block Error Probability	0	0	3.0x10^{-5}*	1	2	7	560
Block Misdelivery Probability	-	-	-	-	-	-	-
Extra Block Probability	0	0	3.0x10^{-2}*	1	2	7	560
Block Loss Probability	0	0	3.0x10^{-2}*	1	2	7	560
Transfer Denial Probability	0	0	5.0x10^{-2}*	1	2	7	273
Source Disengagement Time (s)	13.2	13.5	13.8	1	2	7	102
User Fraction of Source Disengagement Time	0.064	0.067	0.072	1	2	7	102
Source Disengagement Denial Probability	0.042	0.081	0.144	1	2	7	111
Destination disengagement Time (s)	3.3	3.5	3.7	2	2	7	111
User Fraction of Destination Disengagement Time	0.170	0.185	0.200	2	2	7	111
Destination Disengagement Denial Probability	0	0	0.114*	1	2	7	111

* Conditional probability assumed to be 0.8
\- Not measured

** 1 means no significant difference among tests or cities, so all trials pooled.
2 means no significant difference among cities, so all test means pooled.
3 means significant difference among cities, so no pooling; only 1 or 2 degrees of freedom for confidence limit.

Table 7. Summary of Performance Parameter Estimates for Network D Connections

Performance Parameter Summary For Network D Connections

Performance Parameter	*95% Lower Limit*	*Mean Estimate*	*95% Upper Limit*	*Pooling Disposition***	*Number of Cities*	*Number of Tests*	*Number of Trials*
Access Time (s)	35.4	35.6	35.8	1	1	2	40
User Fraction of Access Time	0.039	0.042	0.045	1	1	2	40
Incorrect Access Probability	0	0	0.251*	1	1	2	40
Access Outage Probability	0	0	0.251*	1	1	2	40
Access Denial Probability	0	0	0.251*	1	1	2	40
Block Transfer Time (s)	1.39	1.41	1.42	1	2	4	320
User Fraction of Block Transfer Time	0.093	0.093	0.094	1	2	4	320
User Fraction of Input/Output Time	0.250	0.250	0.251	1	2	4	4
User Information Bit Transfer Rate (bps)	952	952	952	1	2	4	4
Bit Error Probability	0	0	5.0×10^{-5}*	1	2	4	327680
Bit Misdelivery Probability	-	-	-	-	-	-	-
Extra Bit Probability	0	0	5.0×10^{-5}*	1	2	4	327680
Bit Loss Probability	0	0	5.0×10^{-5}*	1	2	4	327680
Block Error Probability	0	0	4.0×10^{-2}*	1	2	4	320
Block Misdelivery Probability	-	-	-	-	-	-	-
Extra Block Probability	0	0	4.0×10^{-2}*	1	2	4	320
Block Loss Probability	0	0	4.0×10^{-2}*	1	2	4	320
Transfer Denial Probability	0	0	8.0×10^{-2}*	1	2	4	156
Source Disengagement Time (s)	2.8	3.2	3.6	2	1	2	40
User Fraction of Source Disengagement Time	0.230	0.263	0.295	2	1	2	40
Source Disengagement Denial Probability	0	0	0.251*	1	1	2	40
Destination Disengagement Time (s)	0.52	0.69	0.86	2	1	2	40
User Fraction of Destination Disengagement Time	0.602	0.821	1.04	2	1	2	40
Destination Disengagement Denial Probability	0	0	0.251*	1	1	2	40

* Conditional probability assumed to be 0.8
- Not measured

** 1 means no significant difference among tests or cities, so all trials pooled.
2 means no significant difference among cities, so all test means pooled.
3 means significant difference among cities, so no pooling; only 1 or 2 degrees of freedom for confidence limit.

Table 8. Summary of Performance Parameter Estimates for Network F Connections

Performance Parameter Summary For Network F Connections

Performance Parameter	*95% Lower Limit*	*Mean Estimate*	*95% Upper Limit*	*Pooling Disposition***	*Number of Cities*	*Number of Tests*	*Number of Trials*
Access Time (s)	41.4	42.2	42.9	2	1	4	76
User Fraction of Access Time	0.034	0.035	0.036	2	1	4	76
Incorrect Access Probability	0	0	0.150*	1	1	4	80
Access Outage Probability	0	0	0.150*	1	1	4	80
Access Denial Probability	0.016	0.050	0.122	1	1	4	80
Block Transfer Time (s)	NA	NA	NA	-	-	-	-
User Fraction of Block Transfer Time	NA	NA	NA	-	-	-	-
User Fraction of Input/Output Time	NA	NA	NA	-	-	-	-
User Information Bit Transfer Rate (bps)	NA	NA	NA	-	-	-	-
Bit Error Probability	NA	NA	NA	2	2	7	572168
Bit Misdelivery Probability	NA	NA	NA	-			
Extra Bit Probability	NA	NA	NA	1	2	7	572168
Bit Loss Probability	NA	NA	NA	1	2	7	573440
Block Error Probability	NA	NA	NA	1	2	7	560
Block Misdelivery Probability	NA	NA	NA	-	-	-	
Extra Block Probability	NA	NA	NA	1	2	7	560
Block Loss Probability	NA	NA	NA	1	2	7	560
Transfer Denial Probability	NA	NA	NA	1	2	7	273
Source Disengagement Time (s)	2.8	2.9	3.0	1	1	4	76
User Fraction of Source Disengagement Time	0.246	0.259	0.272	1	1	4	76
Source Disengagement Denial Probability	0	0	0.156*	1	1	4	76
Destination Disengagement Time (s)	0.51	0.56	0.61	1	1	4	76
User Fraction of Destination Disengagement Time	0.846	0.888	0.930	1	1	4	76
Destination Disengagement Denial Probability	0	0	0.156*	1	1	4	76

* Conditional probability assumed to be 0.8
\- Not measured

** 1 means no significant difference among tests or cities, so all trials pooled.
2 means no significant difference among cities, so all test means pooled.
3 means significant difference among cities, so no pooling; only 1 or 2 degrees of freedom for confidence limit.

- Incorrect Access Probability. No Incorrect Access failures were observed, therefore the estimated probability was zero for connections over all networks.

- Access Outage Probability. This type of failure was observed only in connections over PDN B (with an estimated probability of 0.046). Each trial resulting in Access Outage was preceded by a trial resulting in source Disengagement Denial.

- Access Denial Probability. No Access Denial failures were observed in connections over network D. Otherwise, the estimated Access Denial Probability was generally 0.007-0.02. As discussed in Section 5.2.4, these failures had a propensity to occur later in the tests: 80% of the Access Denial failures occurred in trials 11-20 (each test consisted of 20 trials). Although this trend was associated with local telephone connection failures, the cause is not known.

5.1.2 User Information Transfer Parameters

User information transfer parameter estimates presented in the summary tables are based on high-utilization, flow-controlled tests that transferred 128-character blocks. (No tests over connections using network F were conducted under these conditions.)

- Block Transfer Time. Block Transfer Time was shortest for connections over network D (1.41 seconds). Transfer via connections over PDNs A and B generally required about 4 seconds. For connections utilizing PDN C, dependence between successive block transfer times was very strong (the autocorrelation of lag 1 was about 0.97). This resulted in a small number of effective degrees of freedom and a large confidence interval.

- User Fraction of Block Transfer Time. This fraction was generally 0.09-0.10.[3]

- User Fraction of Input/Output Time. This fraction was generally 0.21-0.25.[3]

- User Information Bit Transfer Rate. This rate was 814-906 bps for connections over the PDNs and 952 bps for connections over network D.

- Bit Error Probability. Bit errors were observed only in tests on connections over PDN A with an estimated probability of 7×10^{-6}. As discussed in Section 5.3.3, these bit errors were

[3]As discussed in Section 5.3.7, measured values of this parameter did not accurately describe the effect of user delay on total performance time.

almost certainly introduced in the remote terminal access lines, as these were not protected by error control.

- Bit Misdelivery Probability. This performance parameter was not measured.

- Extra Bit Probability. No extra bits were observed; hence, the estimated probability was zero for connections over all networks.

- Bit Loss Probability. Bit loss was observed only in tests on connections over network F. The estimated probability was 2×10^{-3}.

- Block Error Probability. Block errors were observed only in tests on connections over PDN A and network F. The estimated probability was 2×10^{-3} for PDN A connections and 5×10^{-3} for network F connections.

- Block Misdelivery Probability. This performance parameter was not measured.

- Extra Block Probability. No extra blocks were observed; hence, the estimated probability was zero for connections over all networks.

- Block Loss Probability. No lost blocks were observed; hence, the estimated probability was zero for connections over all networks.

- Transfer Denial Probability. Transfer Denial was observed only in tests on connections over network F, with an estimated probability of 7×10^{-3}.

5.1.3 Disengagement Parameters

The disengagement parameter estimates presented in the summary tables are based on the same tests used to estimate access parameters. Separate sets of disengagement parameter values were calculated for source and destination users.

- Source Disengagement Time. Disengagement of the source user required 12.8-15.1 seconds for connections over the PDNs and 2.9-3.2 seconds for connections over networks D and F.

- User Fraction of Source Disengagement Time. This fraction was 0.061-0.070 for connections over the PDNs and 0.259-0.263 for connections over networks D and F. The larger fractions reflected shorter disengagement times.

- Source Disengagement Denial Probability. Source Disengagement Denial failures were observed only in tests on connections over the PDNs. The estimated probabilities were 0.072-0.085.

- Destination Disengagement Time. Disengagement of the destination user required 2.5-5.2 seconds for connections over the PDNs and 0.69-0.56 seconds for connections over networks D and F.

- User Fraction of Destination Disengagement Time. This fraction was 0.128-0.251 for connections over the PDNs and 0.821-0.888 for connections over networks D and F. As in the case of source disengagement, the larger fractions reflect shorter disengagement times.

- Destination Disengagement Denial Probability. Destination Disengagement Denial was observed only in tests on connections over PDN A, with an estimated probability of 0.018.

5.2 Access and Disengagement Performance

Results described in this section are based on the 51 access-disengagement tests listed in Table 9. The first column specifies the test number and the second column specifies the location of the remote terminal. Two tests were conducted from Ft. Worth (ftw), 16 from Seattle (sea), 21 from Washington, DC (wdc), and 12 from Denver (den). The third column indicates the network that was used, the fourth column lists the day of the week the test was conducted, the fifth column lists the time period of the test, the sixth column specifies the size of the user information block transferred (L denotes long (128-character) blocks), the seventh column indicates whether flow control was enabled (f-on) or not enabled (f-off), and the eighth column lists the dialing method (tone or pulse). Although they are listed in the table, the block size and flow control status did not affect access or disengagement parameters.

Values were measured for all access and disengagement parameters defined in ANS X3.102, and separate disengagement parameter values were measured for source and destination users. Results for each measured parameter are described in the subsections that follow.

5.2.1 Access Time

Access Time is the average time between an end user's request for communication service and the start of user information transfer. The start of access corresponded to the issuance of a command to dial the local phone number of the relevant PDN or the number of the Boulder host. The end of access

Table 9. Access-Disengagement Tests Used in Data Analysis

Test	Test Conditions
775	ftw A fri 1 L foff tone
779	ftw B fri 2 L f-on tone
790	sea B thu 2 L f-on tone
796	sea C thu 3 L foff tone
800	sea F thu 3 L foff tone
811	sea A thu 5 L foff tone
815	sea A fri 6 L foff tone
819	sea F fri 1 L foff tone
823	sea A fri 2 L foff tone
831	sea B mon 2 L f-on tone
835	sea A mon 3 L foff tone
845	sea F wed 3 L foff tone
850	sea B wed 5 L f-on tone
854	sea B thu 6 L f-on tone
858	sea A thu 1 L foff tone
867	sea B thu 3 L f-on tone
876	sea A thu 4 L foff tone
880	sea F thu 5 L foff tone
891	wdc C sun 5 L f-on puls
895	wdc C mon 6 L f-on puls
899	wdc F mon 1 L foff puls
907	wdc B mon 3 L f-on tone
915	wdc C mon 4 L f-on tone
919	wdc C mon 5 L f-on tone
928	wdc A tue 1 L foff tone
932	wdc B tue 2 L f-on tone
936	wdc C tue 3 L f-on tone
941	wdc D tue 4 L foff tone
952	wdc A tue 5 L f-on tone
964	wdc B wed 2 L f-on tone
969	wdc C wed 2 L f-on tone
973	wdc D wed 3 L foff tone
978	wdc A wed 4 L f-on tone
982	wdc B wed 5 L f-on tone
986	wdc B thu 6 L f-on tone
995	wdc C thu 3 L f-on tone
997	wdc A thu 3 L f-on tone
1003	wdc B thu 4 L f-on tone
1008	wdc C thu 5 L f-on tone
1014	den C tue 5 L f-on puls
1018	den C wed 6 L f-on puls
1027	den A wed 2 L f-on puls
1031	den B wed 3 L f-on puls
1035	den C wed 4 L f-on puls
1047	den B thu 1 L f-on puls
1053	den C thu 2 L f-on puls
1062	den A thu 4 L f-on puls
1066	den A thu 5 L f-on puls
1070	den B fri 6 L f-on puls
1075	den C fri 1 L f-on puls
1083	den B fri 2 L f-on puls

corresponded to the issuance of a command to write the first block of user information to the network.

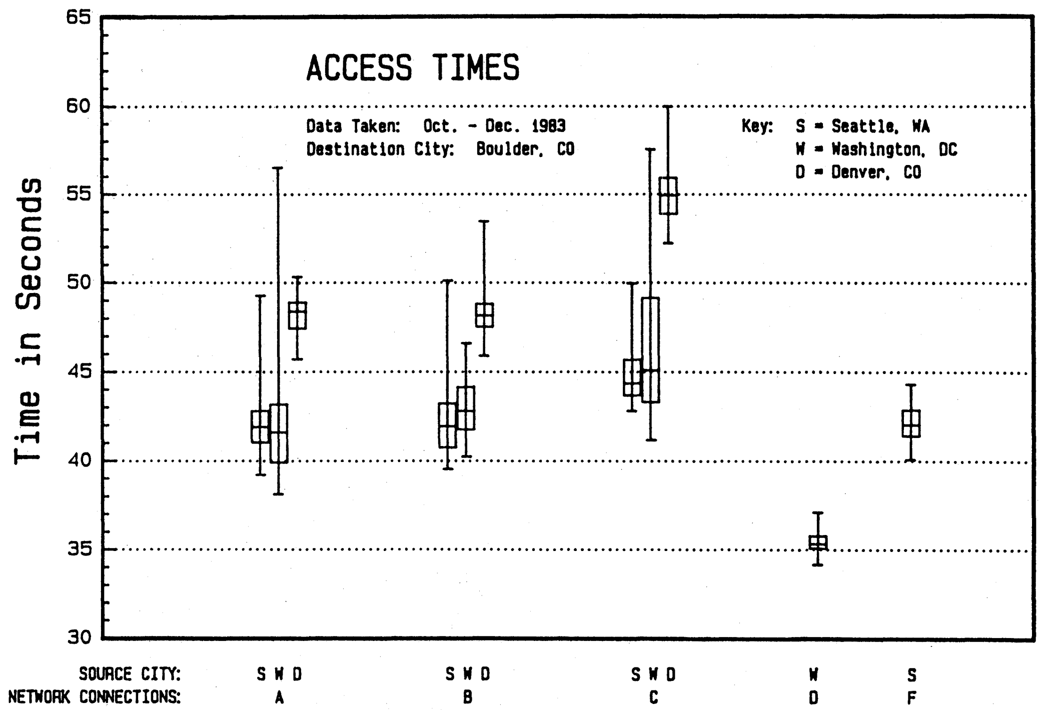
Measurements of access times are summarized by two sets of box plots in Figure 20. In the first, the plots are clustered by network and show the expected result that access times for connections over the telephone networks D or F were generally shorter than those over a PDN. Box plots in the second set are clustered by city and show the surprising result that longer access times generally occurred on the Denver-to-Boulder link. One would normally expect access times to be shorter in tests conducted from Denver. The explanation of the longer times is that all Denver tests used a dc pulse (rotary) dialing system, whereas dual-tone multiple-frequency (DTMF) dialing was generally used elsewhere. The contrast between DTMF and dc-pulse dialing is shown in Figure 21 by two histograms of access times measured for connections over PDN C from Washington, DC. The difference in the means for these two automatic dialing systems is about 9.5 seconds.

Histograms of access times for connections over PDN B and network D from Washington, DC, are shown in Figure 22. The larger values for the PDN connections may be attributed to two factors:

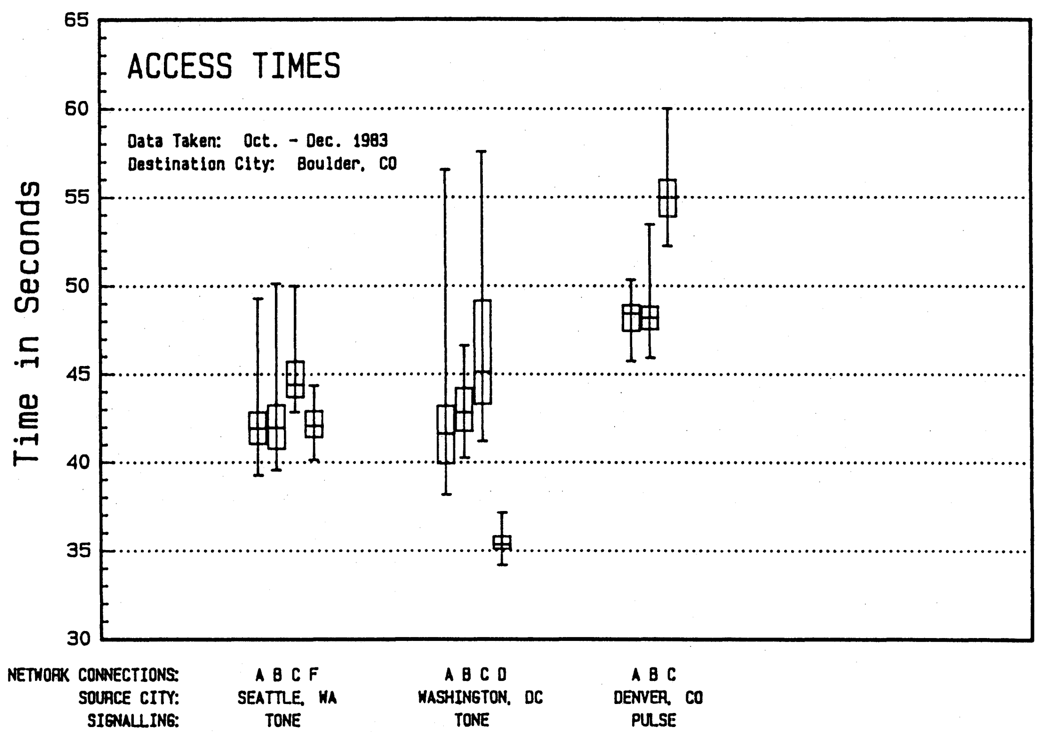
- the PDN login time (which has no counterpart in network D) and
- a longer host computer login time for PDN connections because of longer transit delays and lower throughput.

Figure 23 shows histograms of overall access delay and its component values for selected tests on connections over PDN B from Washington, DC. Local telephone connection time began with the issuance of the command to dial the local telephone number of the PDN and ended with the receipt of the subsequent CONNECT response. This component accounted for 37% of the overall access delay. PDN login and connection time began with the issuance of a command to "wake up" the PDN and ended with the receipt of a response indicating that connection to the host had been completed; it accounted for 9% of the overall access delay. Host login time, which began with the issuance of the user name and ended with the receipt of the READY response from the RECV program, accounted for 53% of the overall access delay. The remaining 1% of the access delay (indicated by hachured bars in the figure) was user delay during which the XMIT and RECV programs performed interface monitor functions.

These results suggest that a large proportion of the access delay experienced by public data network users is a result of factors outside the PDN

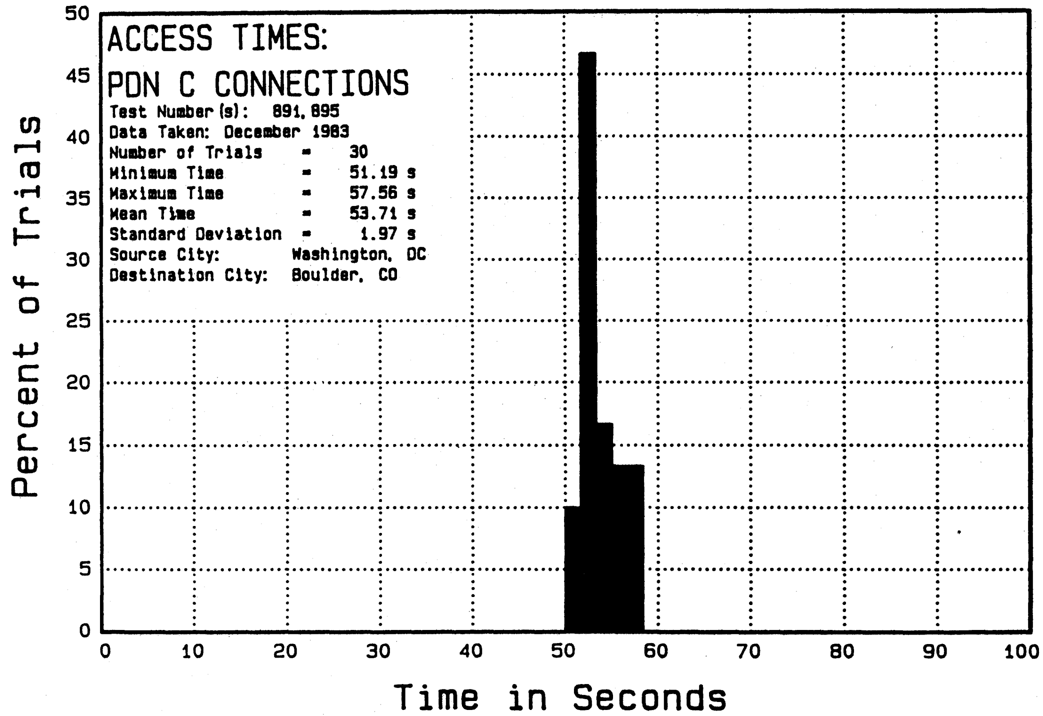


a. Plots Clustered by Network

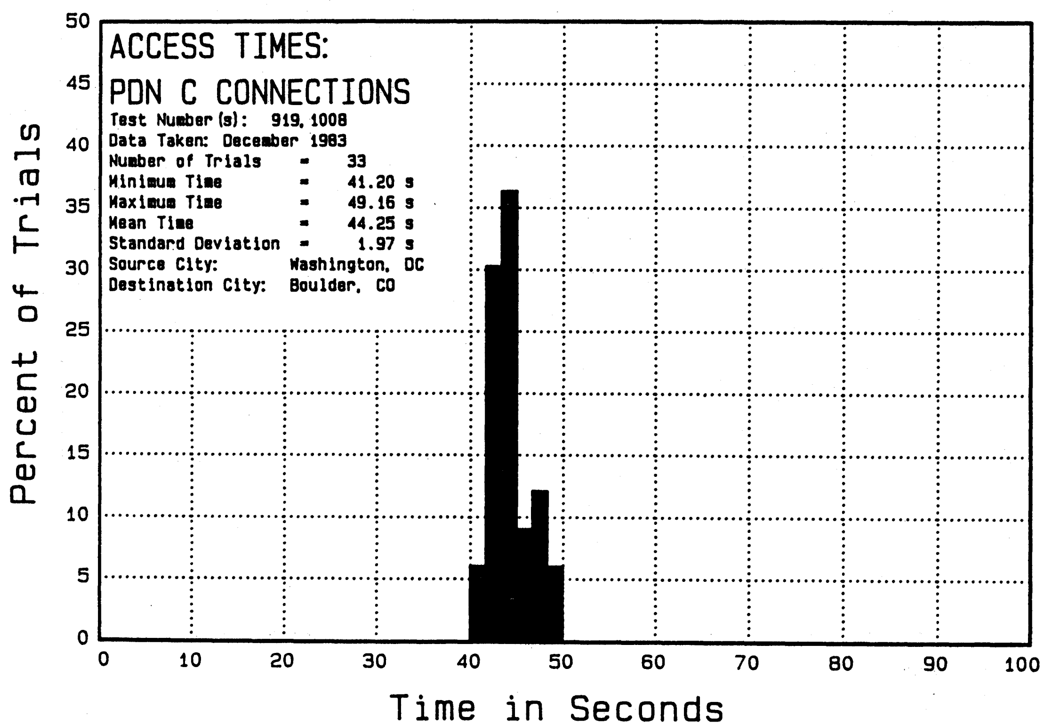


b. Plots Clustered by City

Figure 20. Access time box plots.

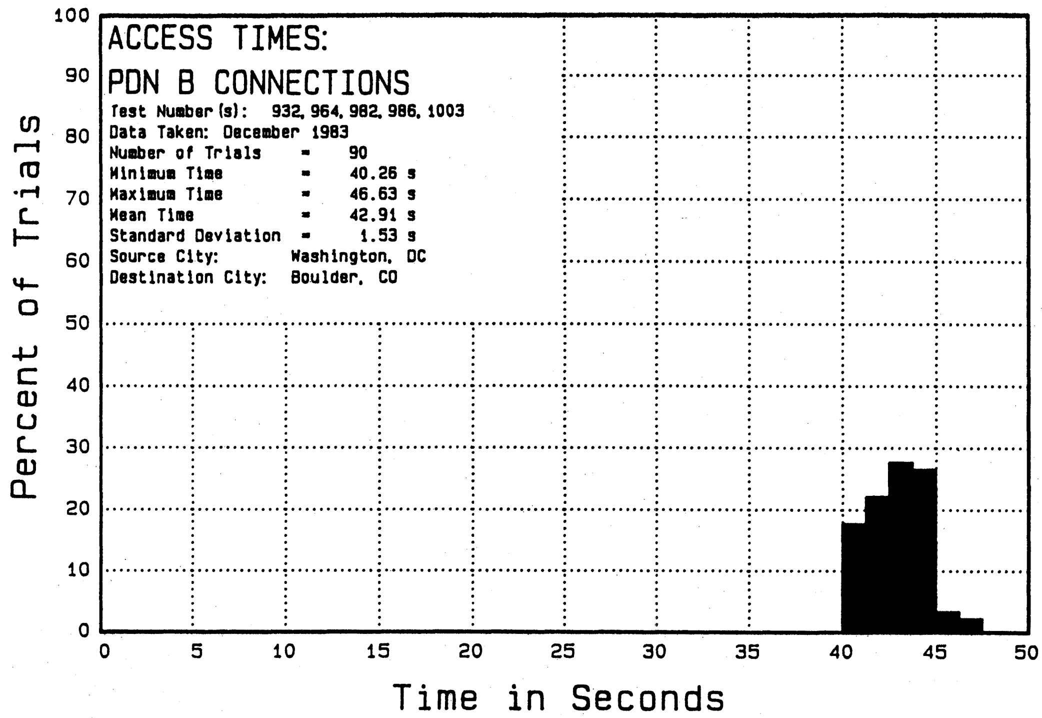


a. Pulse Dialing Results

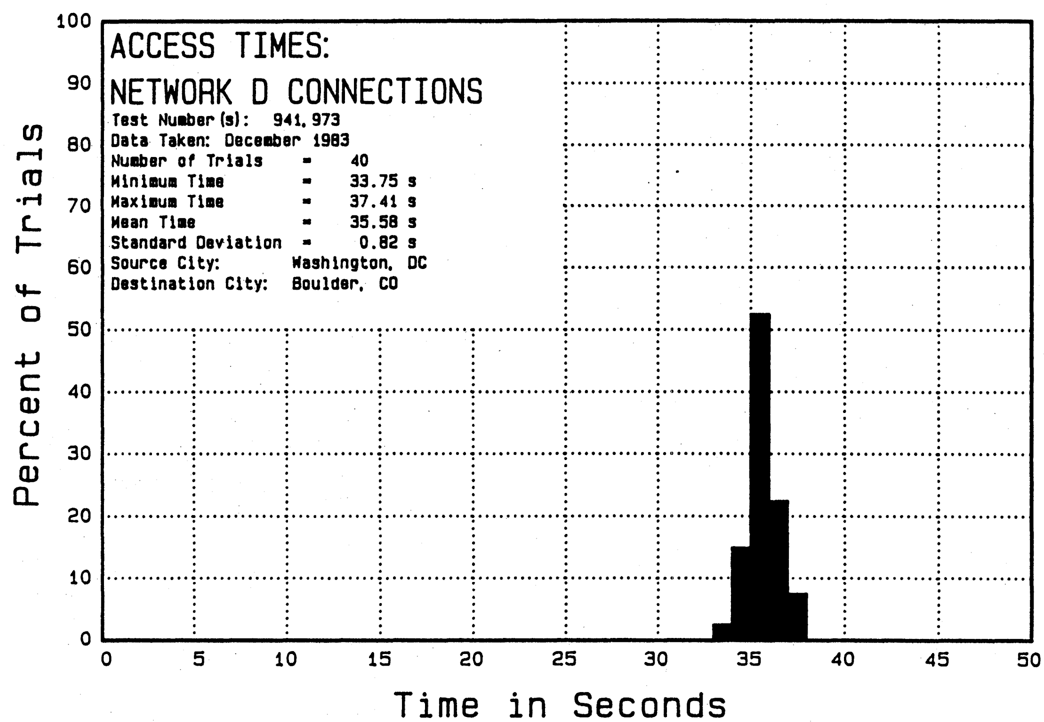


b. Tone Dialing Results

Figure 21. Effect of dialing system on access time.



a. Results for PDN B Connections



b. Results for Network D Connections

Figure 22. Comparison of access times for PDN and PSTN connections.

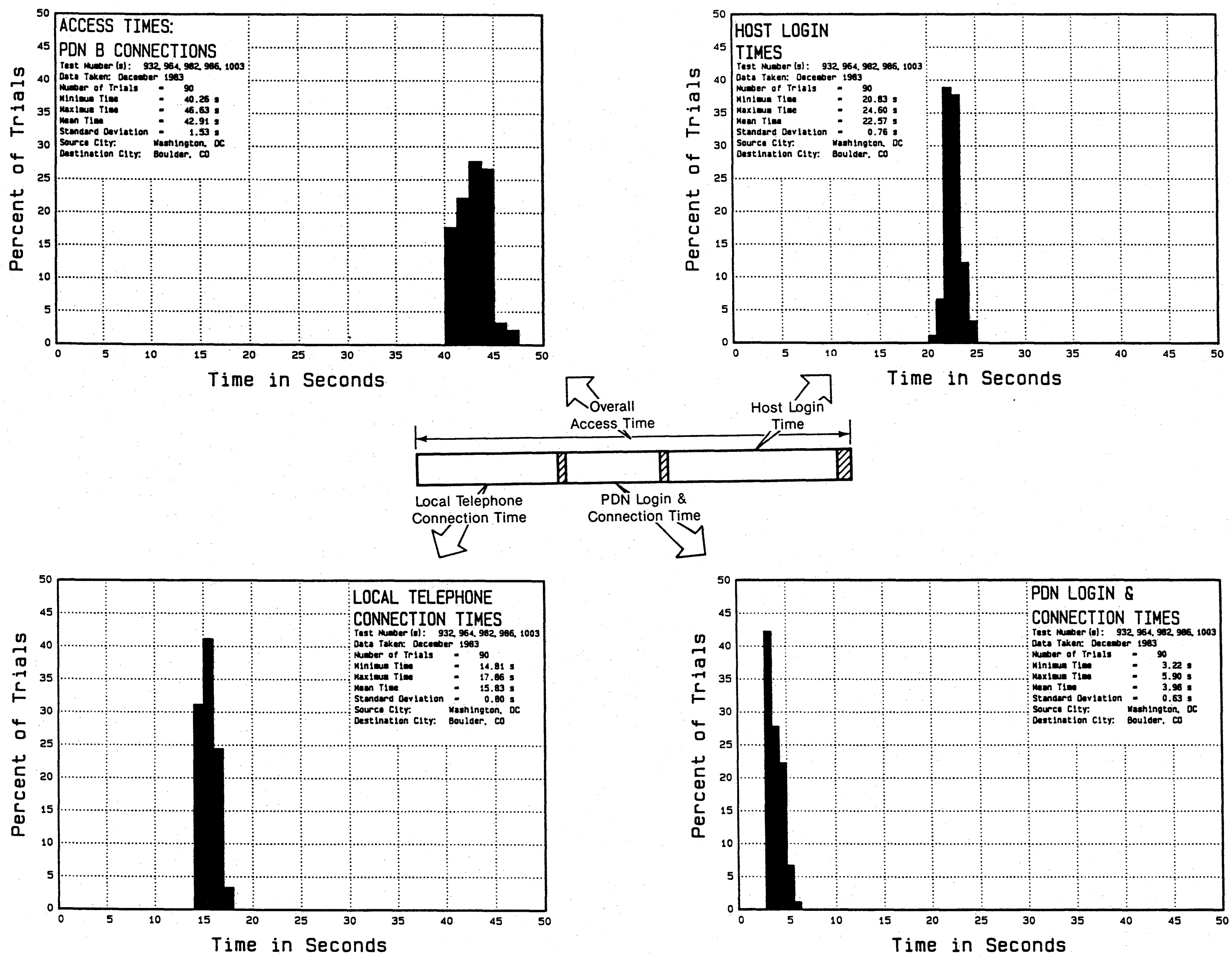


Figure 23. Components of access time for PDN connections.

boundaries, thus outside the control of the PDN service provider. Even if host computer login time were excluded, the access delays outside the PDN would still be more than four times greater than those within it. An obvious implication is that efforts to reduce the PDN connection time (e.g., transit delay for X.25 Call Request and Call Accepted packets) will do little to improve the customer's perception of service quality. The access times experienced by PDN users can, of course, be reduced substantially through the use of leased (rather than switched) terminal access arrangements.

Figure 24 shows typical chronological plots of virtual circuit connection times utilizing PDNs A, B, and C from Washington, DC. Virtual circuit connection time began with the issuance of the host's address by XMIT and ended with the receipt of the host login prompt.

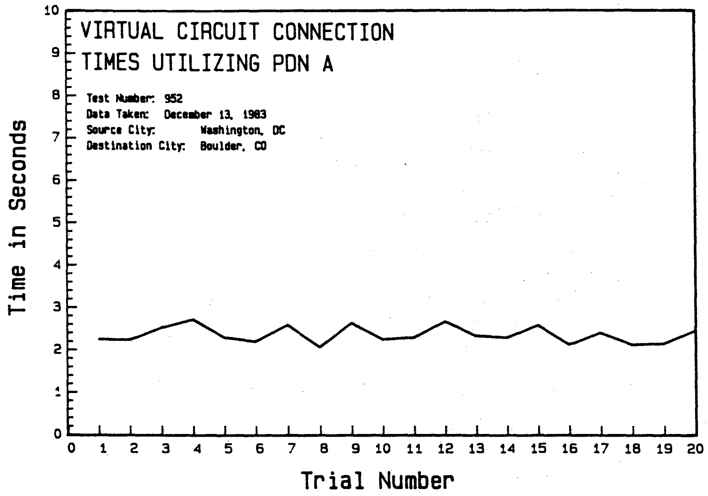
Figure 25 presents chronological plots of observed access times for typical tests on connections over the PDNs and network D from Washington, DC. Each test was conducted using DTMF dialing. The plots indicate that access times for PDN C connections were longer and more variable than those for PDN A and PDN B connections; this indication is confirmed by the box plots in Figure 20a. The chronological plots also illustrate that access times for connections over network D were significantly lower than those for connections over the PDNs. The plots do not show any obvious dependence between successive trials. Note that this figure includes the same tests as those used in the plots of virtual circuit connection times in Figure 24.

5.2.2 User Fraction of Access Time

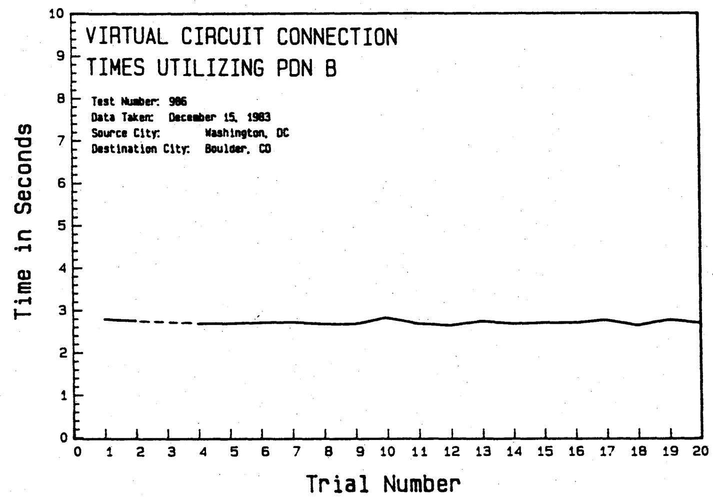
User Fraction of Access Time is the ratio of the average access time for which a user is responsible to the average total performance time for access attempts that result in Successful Access. In a connection-oriented session, an access attempt is successful if user information transfer begins within the maximum performance period and the nonoriginating user is committed to the session prior to the start of user information transfer.

In the tests conducted by ITS, measured user delays associated with the access function were produced by two application program activities:

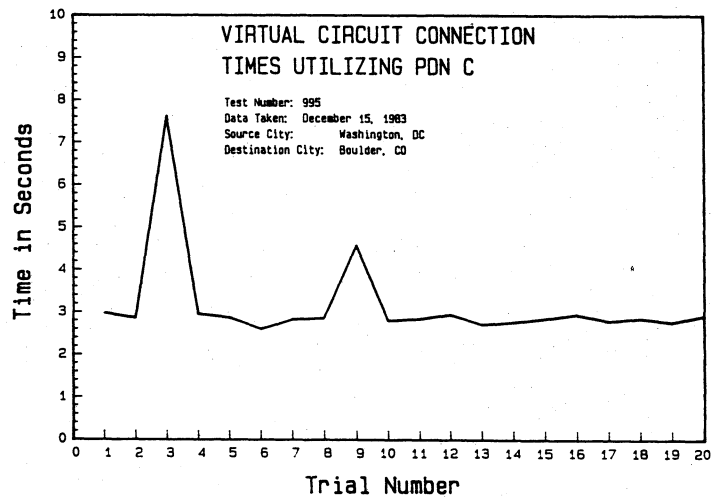
- carrying out initialization procedures (e.g., opening files) by RECV at the start of a session and
- reading the satellite clock to obtain times for recorded events at the source and destination interfaces (both interfaces are relevant in access performance time allocation).



a. Results for PDN A Connections

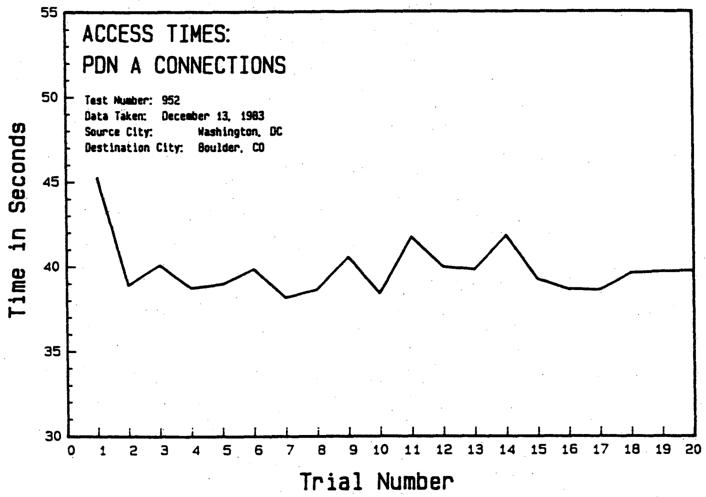


b. Results for PDN B Connections

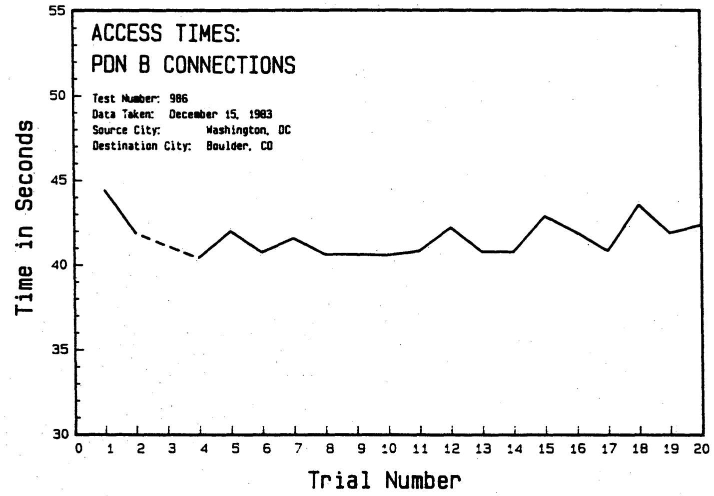


c. Results for PDN C Connections

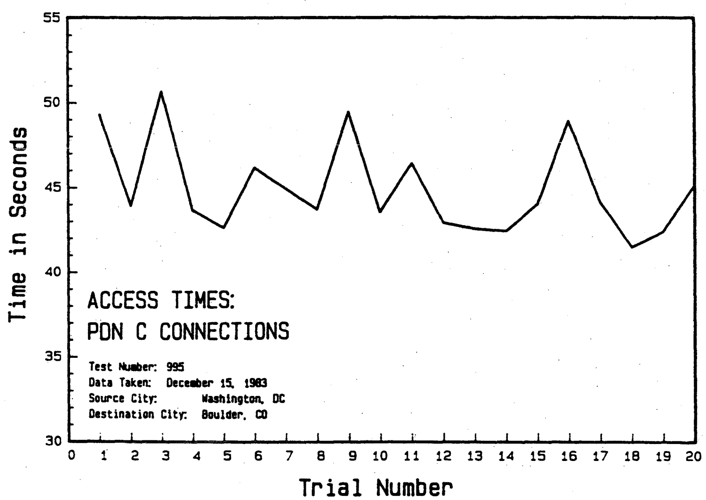
Figure 24. Virtual circuit connection time chronological plots.



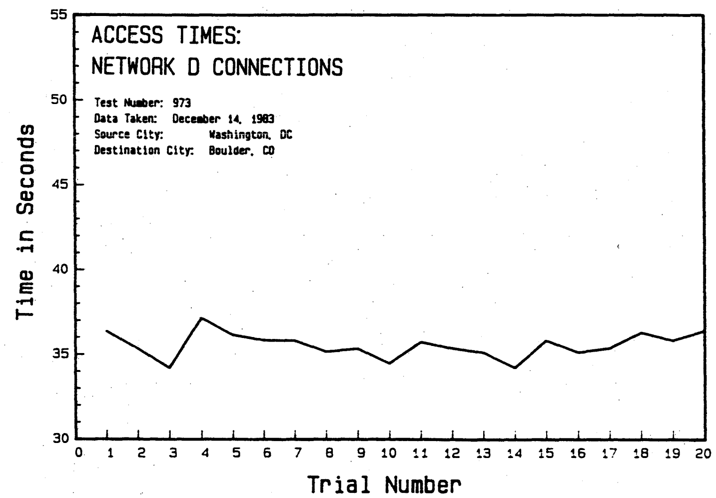
a. Results for PDN A Connections



b. Results for PDN B Connections



c. Results for PDN C Connections



d. Results for Network D Connections

Figure 25. Access time chronological plots.

These delays were largely determined by measurement system characteristics and were not appreciably affected by any of the performance factors identified in the experiment. Most of the variation in observed user delay was associated with the initialization procedures performed by RECV. Within a test, startup delays for successive access attempts formed a pattern in which the delay for the first attempt was in the interval 1.6-1.9 seconds and delays for most subsequent attempts were closely clustered in a much smaller interval, 0.65-0.80 seconds. (The RECV program performed more initialization procedures for the first session in a test than for subsequent sessions.) Infrequently, startup delays during an initial or subsequent access attempt were substantially above the typical range. Reasons for this are not clear.

Despite the fluctuations just noted, variations in the average user performance time (within tests) were small compared to variations in the average total performance time. Thus, variations in measured values of both Access Time and User Fraction of Access Time were largely the result of variations in system performance time. Measured values of User Fraction of Access Time are summarized in Table 10 for several categories of measurement conditions. Parameter estimates and associated information for individual tests are presented in Appendix G.

Table 10. Summary of Measured Values of User Fraction of Access Time

Measurement Conditions (Dialing method:Network connections)	Access Time (seconds)	User Fraction of Access Time
Tone dialing:Network D	35.5-35.6	0.041-0.042
Tone dialing:All PDNs and network F	38.3-45.5	0.032-0.039
Pulse dialing:All networks	47.8-55.5	0.027-0.031

Most of the observed user delay associated with access was a result of interface monitor functions performed by the XMIT and RECV application programs and would not have occurred otherwise. Consequently, values of User Fraction of Access Time obtained in the ITS measurements did not represent typical operating conditions. They did, however, accurately account for the influence of the measurement system on observed values of Access Time.

5.2.3 Incorrect Access Probability

Incorrect Access occurs if the system establishes a connection to a destination other than that intended and does not correct the error prior to the start of user information transfer. Incorrect Access thus corresponds to a "wrong number." Incorrect Access Probability is the (conditional) probability that Incorrect Access occurs in an access attempt that does not result in User Blocking. In a performance measurement, this probability is estimated by the ratio of the number of Incorrect Access outcomes to the total number of access attempts in the measurement sample.

The 51 access-disengagement tests listed in Table 9 included 1020 access trials. None of these trials resulted in Incorrect Access, so the estimated value of Incorrect Access Probability is zero for connections over each network.

5.2.4 Access Denial Probability

Access Denial occurs if the system responds to an Access Request during the maximum performance period, but the attempt fails as a result of a System Blocking Signal or excessive system delay. Access Denial Probability is the (conditional) probability that Access Denial occurs in an access attempt that does not result in User Blocking. In a performance measurement, this probability is estimated by the ratio of the number of Access Denial outcomes to the total number of access attempts in the measurement sample.

Estimated values of Access Denial Probability are plotted in Figure 26 for each of the 51 access-disengagement tests. All Access Denial outcomes observed in the ITS measurements resulted from the failure of the XMIT program to detect the expected response to a command issued during the access procedure. When such a failure occurred, the program wrote a message to the LOG.X file that indicated the point in the access procedure at which the failure occurred. From these data, it was possible to classify Access Denial outcomes in one of the following four categories:

- o local telephone connection failures,
- o PDN login failures,
- o host connection failures, and
- o host login failures.

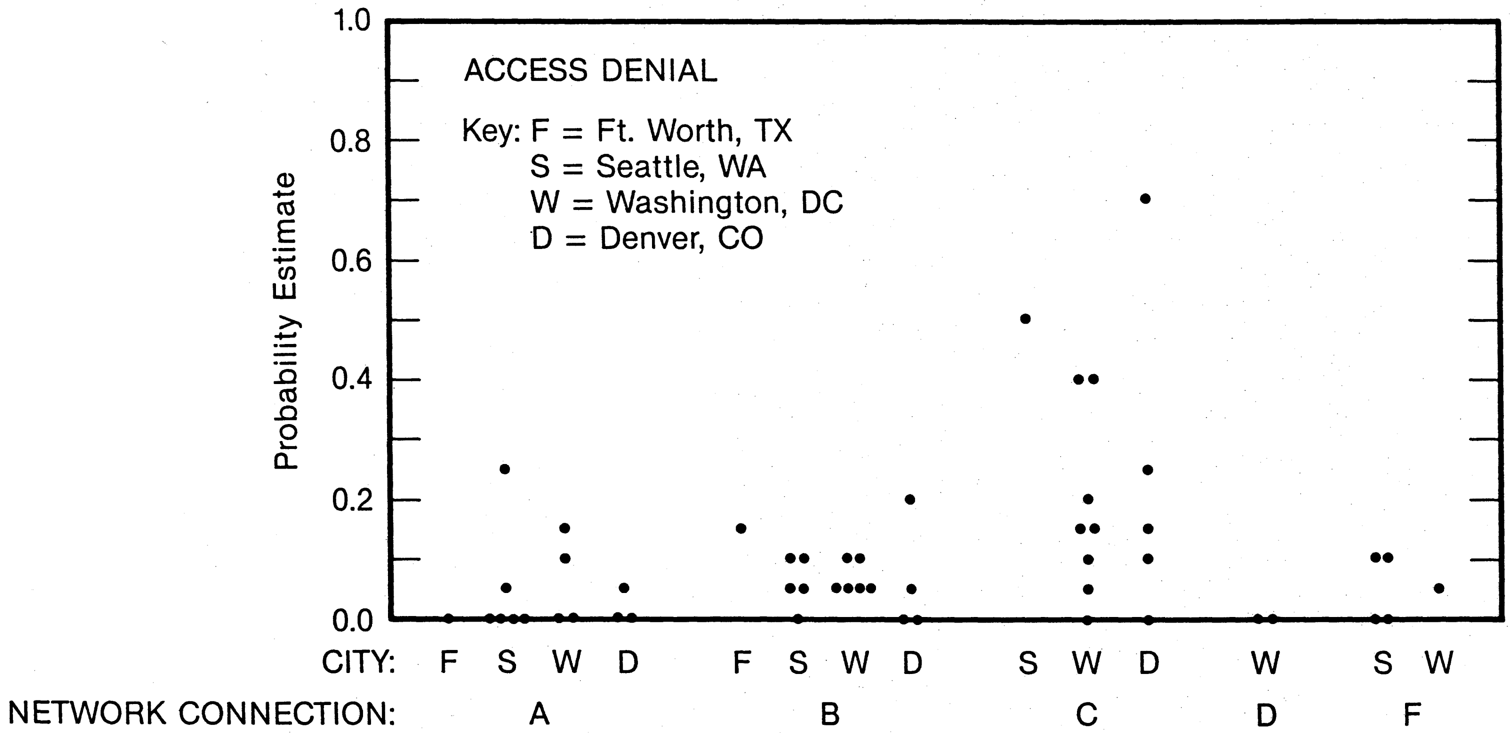


Figure 26. Access denial probability plots.

Table 11 shows all access and disengagement failures observed in the 51 access-disengagement tests and indicates the category of each Access Denial outcome. Of the 1020 trials, 11.7% resulted in Access Denial. Figure 27 summarizes data in Table 11 by indicating the percent of access failures in each category for the PDN and FTS (network F) connections. The FTS results may be somewhat misleading, since only three local telephone connection failures were observed during four tests (80 trials) using this network. No failures were observed during the two tests (40 trials) that were conducted using the public switched telephone network.

The number of access and disengagement failures appeared to increase as the tests progressed through the 20 trials (see Figure 28). This trend was confirmed by a significance test of the slope of the regression line of the number of failures as a function of trial number (i.e., the slope is 0.1992, the Student t statistic is 2.232, and the 5% point of the Student t distribution is 2.101).

The number of failures for each of the seven types of access and disengagement failures was plotted as a function of trial number. The plots revealed that the local telephone connection failures were the primary (and, probably the only) source of this trend (i.e., the slope is 0.099, the Student t statistic is 2.837, and the 5% point of the Student t distribution is 2.101).

Not only did nearly 80% of these 24 failures occur in the second half of the tests, but there was substantial serial dependence (i.e., there were 24 failures and 8 pairs of consecutive failures). There was no noticeable tendency of these failures to vary with test conditions such as network connection, time of day, day of week, or type of signaling. The cause of this unsuspected "fatigue" effect is not known.

Table 12 lists data from all tests having one or more local telephone connection failures. It shows local telephone connection failures (denoted by asterisks) as a function of trial number. Every fifth trial is denoted by a colon, and other trials are denoted by periods. The test number and the levels of five factors are also listed.

Table 11. Access and Disengagement Failures

SESSION / TEST	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
775_A										$d1_\ell$										
779_B																		$a_{\ell 1}$	$a_{\ell 1}$	$a_{\ell 1}$
790_B																				
796_C		$d1_\ell$	$a_{\ell 2}$	$a_{\ell 2}$		$d1_\ell$	$a_{\ell 2}$	$a_{\ell 2}$			$a_{\ell 4}$	$a_{\ell 3}$		$a_{\ell 2}$			$a_{\ell 2}$	$d1_\ell$	$a_{\ell 2}$	$a_{\ell 2}$
800_F																				
811_A															$a_{\ell 2}$					
815_A							$d1_\ell$	$d1_\ell$			$d1_\ell$									
819_F																				
823_A									$d1_\ell$											
831_B		$d1_\ell$	$a_{\ell 2}$	a_o																
835_A											$a_{\ell 1}$	$a_{\ell 1}$	$a_{\ell 2}$	$a_{\ell 2}$	$a_{\ell 1}$					
845_F								$a_{\ell 1}$					$a_{\ell 1}$							
850_B					$d1_\ell$	$a_{\ell 2}$	a_o							$d1_\ell$	$a_{\ell 2}$	a_o				
854_B					$d1_\ell$	$a_{\ell 2}$	a_o		$d1_\ell$	$a_{\ell 2}$	a_o					$d1_\ell$	a_o			
858_A			$d1_\ell$								$d1_\ell$									$d1_\ell$
867_B						$d1_\ell$	$a_{\ell 2}$	a_o												$d1_\ell$
876_A																				$d1_\ell$
880_F															$a_{\ell 1}$			$a_{\ell 1}$		
891_C							$a_{\ell 2}$										$a_{\ell 2}$			
895_C							$a_{\ell 2}$	$a_{\ell 2}$		$d1_\ell$	$a_{\ell 2}$			$a_{\ell 2}$	$a_{\ell 2}$			$a_{\ell 2}$	$a_{\ell 2}$	$a_{\ell 2}$
899_F													$a_{\ell 1}$							
907_B																		$d1_\ell$	$a_{\ell 2}$	a_o
915_C											$d1_\ell$	$a_{\ell 2}$				$a_{\ell 2}$		$a_{\ell 2}$		
919_C										$a_{\ell 2}$			$a_{\ell 2}$			$a_{\ell 2}$				
928_A			$d2_\ell$					$d1_\ell$	$d2_\ell$											
932_B			$d1_\ell$	$a_{\ell 2}$	a_o								$d1_\ell$	$a_{\ell 2}$	a_o	$d1_\ell$				
936_C											$d1_\ell$			$a_{\ell 2}$					$d1_\ell$	
941_D																				
952_A							$d1_\ell$					$d1_\ell$					$d1_\ell$			
964_B									$d1_\ell$		$d1_\ell$			$a_{\ell 1}$		$d1_\ell$				
969_C				$a_{\ell 2}$			$d1_\ell$	$a_{\ell 2}$	$a_{\ell 2}$		$a_{\ell 3}$	$a_{\ell 3}$	$a_{\ell 2}$						$a_{\ell 3}$	$a_{\ell 3}$
973_D																				
978_A						$a_{\ell 1}$		$d1_\ell$				$a_{\ell 2}$								
982_B						$d1_\ell$	$a_{\ell 2}$	a_o												$d1_\ell$
986_B			$a_{\ell 2}$																	
995_C				$d1_\ell$														$d1_\ell$		
997_A					$a_{\ell 1}$						$a_{\ell 1}$		$a_{\ell 1}$				$d1_\ell$			
1003_B	$a_{\ell 1}$																		$d1_\ell$	$a_{\ell 2}$
1008_C		$a_{\ell 2}$				$a_{\ell 2}$					$a_{\ell 2}$				$a_{\ell 2}$					
1014_C	$a_{\ell 2}$		$a_{\ell 2}$												$a_{\ell 2}$					
1018_C																				
1027_A	$a_{\ell 1}$							$d1_\ell$												
1031_B																				
1035_C	$a_{\ell 2}$									$d1_\ell$	$a_{\ell 2}$									
1047_B							$a_{\ell 4}$	$a_{\ell 4}$			$d1_\ell$	$a_{\ell 2}$	a_o			$d1_\ell$	$a_{\ell 2}$	a_o		
1053_C		$d1_\ell$	$a_{\ell 2}$	$a_{\ell 2}$	$d1_\ell$	$a_{\ell 2}$	$a_{\ell 2}$			$a_{\ell 2}$		$a_{\ell 3}$	$a_{\ell 3}$	$a_{\ell 3}$	$a_{\ell 1}$	$a_{\ell 1}$	$a_{\ell 1}$	$a_{\ell 1}$	$a_{\ell 1}$	$a_{\ell 1}$
1062_A				$d1_\ell$														$d1_\ell$	$d1_\ell$	
1066_A	$d1_\ell$	$d1_\ell$													$d1_\ell$	$d1_\ell$				
1070_B	$d1_\ell$	a_o												$d1_\ell$	$a_{\ell 2}$	a_o				
1075_C		$d1_\ell$	$a_{\ell 2}$			$d1_\ell$	$a_{\ell 2}$		$a_{\ell 2}$			$d1_\ell$	$a_{\ell 2}$						$d1_\ell$	$a_{\ell 2}$
1083_B										$d1_\ell$	a_o						$d1_\ell$	a_o		

LEGEND:
- $a_{\ell 1}$—Local Telephone Connection Failure
- $a_{\ell 2}$—PDN Login Failure
- $a_{\ell 3}$—Host Connection Failure
- $a_{\ell 4}$—Host Login Failure

(the four above: Access Denial)

- a_o—Access Outage
- $d1_\ell$—Source Disengagement Denial
- $d2_\ell$—Destination Disengagement Denial

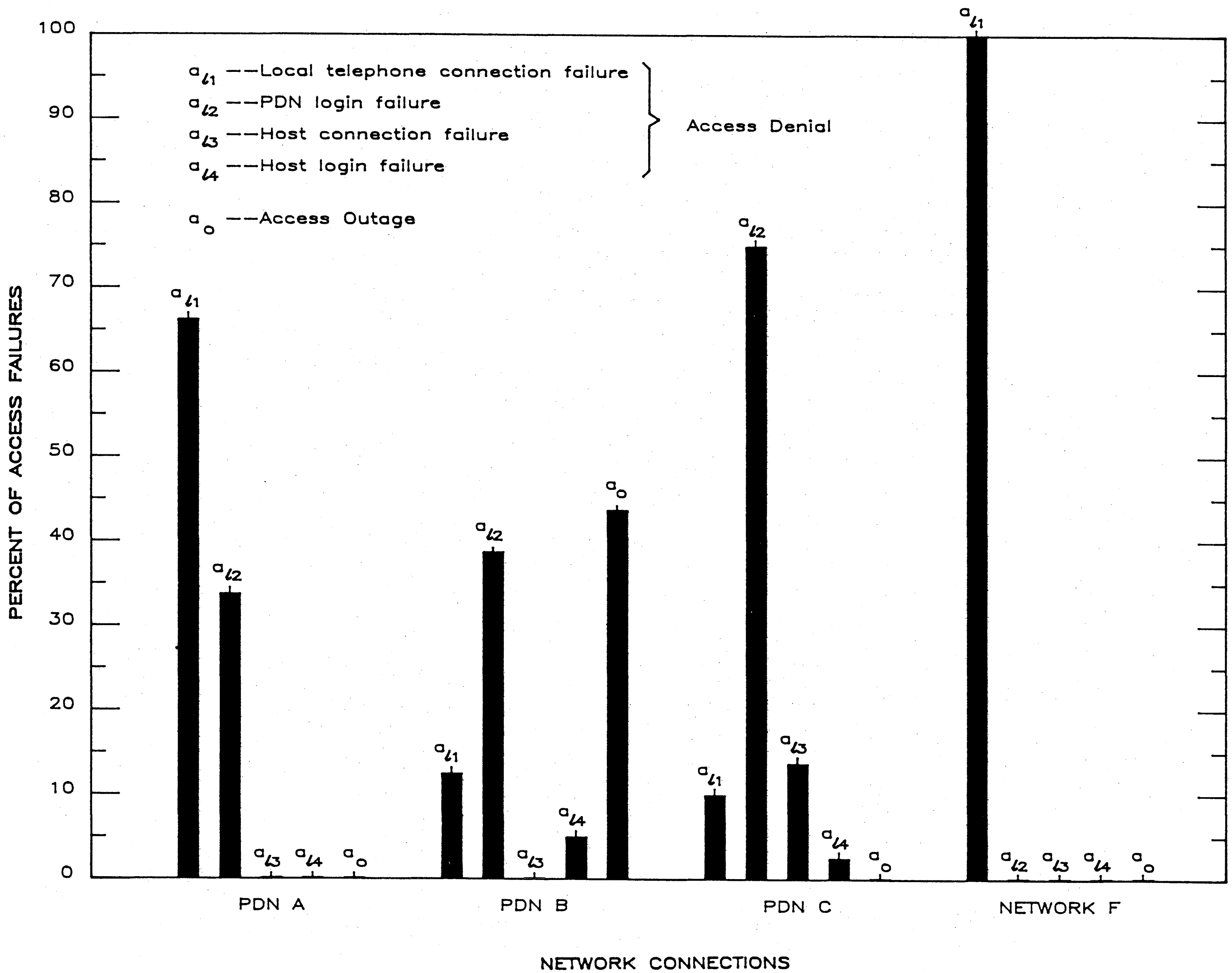


Figure 27. Distribution of access failures for individual networks.

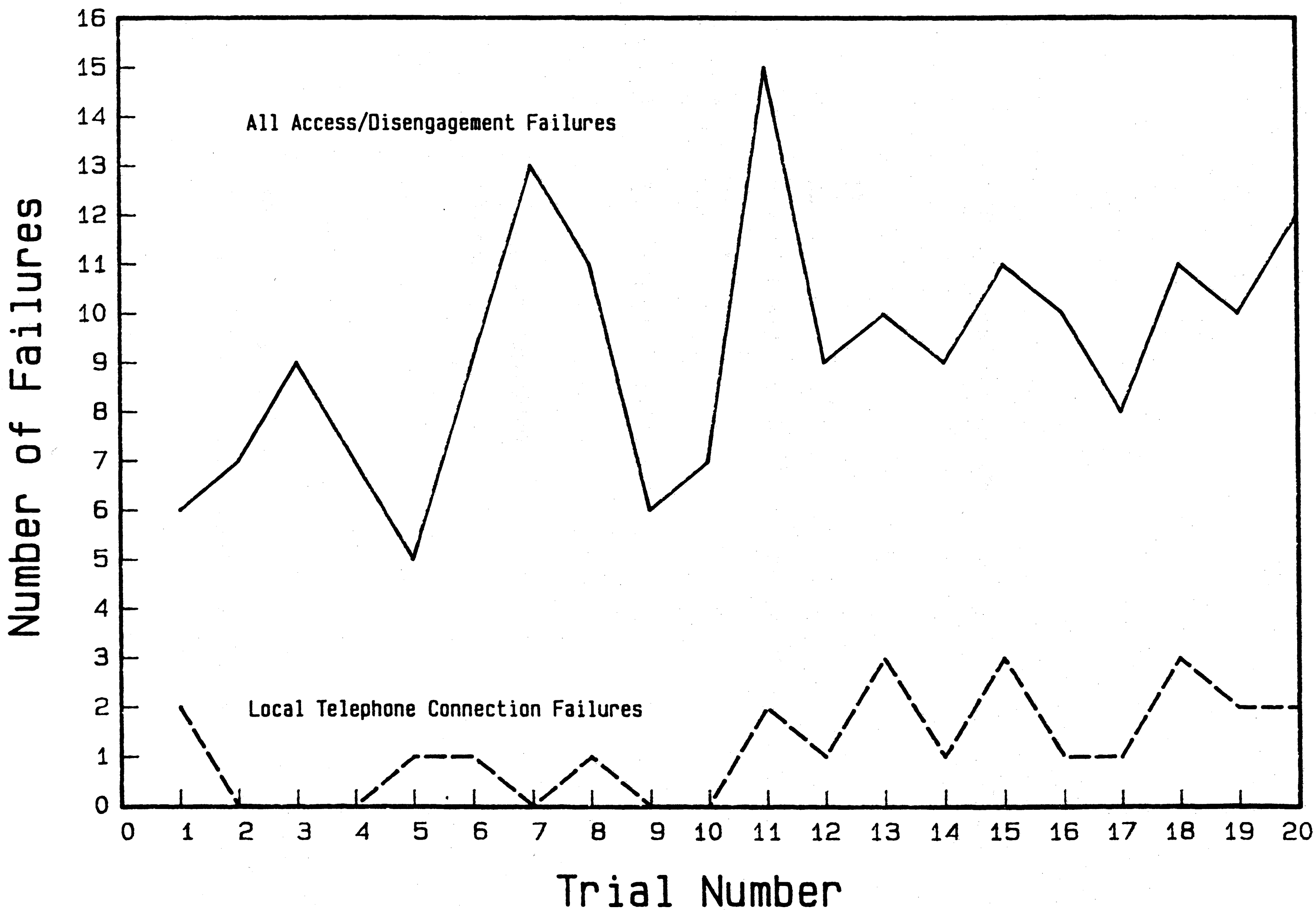


Figure 28. Access and disengagement failures as a function of trial number.

Table 12. Local Telephone Connection Failures

Test Number	City	Network Utilized	Day	Time Period	Signaling Method	
779	ftw	A	fri	1	tone	....:....:....:..***
835	sea	A	mon	3	tone	....:....:**..*....:
845	sea	F	wed	3	tone	....:..*.:..*.:....:
880	sea	F	thu	5	tone	....:....:....*..*.:
899	wdc	F	mon	1	puls	....:....:..*.:....:
964	wdc	B	wed	2	tone	....:....:...*:....:
978	wdc	A	wed	4	tone	....:*...:....:....:
997	wdc	A	thu	3	tone	....*....:*.*.:....:
1003	wdc	B	thu	4	tone	*...:....:....:....:
1027	den	A	wed	2	puls	*...:....:....:....:
1053	den	C	thu	2	puls	....:....:....*****

5.2.5 Access Outage Probability

Access Outage occurs if the system does not respond to an Access Request during the maximum performance period. Access Outage thus implies that the system is "dead" or inoperative for a relatively long period of time. Access Outage Probability is the (conditional) probability that Access Outage occurs in an access attempt that does not result in User Blocking. In a performance measurement, this probability is estimated by the ratio of the number of Access Outage outcomes to the total number of access attempts in the measurement sample.

All Access Outage outcomes observed in the 51 access-disengagement tests occurred in tests on connections over PDN B and appeared to be independent of where the access attempts originated. These outcomes are indicated by the symbol a_o in Table 11. It is important to note that each outage either immediately followed a source disengagement failure or followed successive source disengagement and PDN login failures. This implies that all of the outages were the result of previous disengagement failures. Similar circumstances on connections over other networks did not result in Access Outage (e.g., see test 1075).

5.2.6 Disengagement Time

Disengagement Time is the average value of elapsed time between the start of a disengagement attempt for a particular source or destination user and the successful disengagement of that user. After each successful access attempt, one block consisting of 512 characters was transmitted to the host in Boulder. The disengagement process was then initiated by sending an end-of-text (ETX) character to the destination user. Because the sessions were connection-oriented, the transmission of the ETX character by the source user initiated the disengagement function for both users. The end of disengagement for the destination user occurred when the RECV program terminated after receiving the ETX character. The end of disengagement for the source user occurred when the XMIT program detected the prescribed response to the command that terminated the local telephone connection. Separate disengagement parameters were measured for the source user (the XMIT program) and the destination user (the RECV program).

Figure 29 shows the distribution of both source user and destination user disengagement times for connections over PDN C from Washington, DC. The two populations are clearly distinct: the source distribution is separated from the destination distribution by a gap of more than 10 source standard deviations. The difference between disengagement times for the source and destination users resulted from differences in the nature of the disengagement function at the two interfaces. Source user disengagement included logout from the host computer and disconnection from the PDN, and required four distinct end-to-end transfers of control information. Destination user disengagement was completed prior to logout and disconnection and required only one end-to-end control information transfer. Such asymmetry is typical of modern data communication systems.

Box plots in Figure 30 summarize measured values of source disengagement time. For connections over all PDNs, source disengagement times were slightly lower for Denver. As expected, source disengagement times were much lower for connections over the telephone networks than for connections over the PDNs. This effect is also shown by the histograms in Figure 31. The shorter

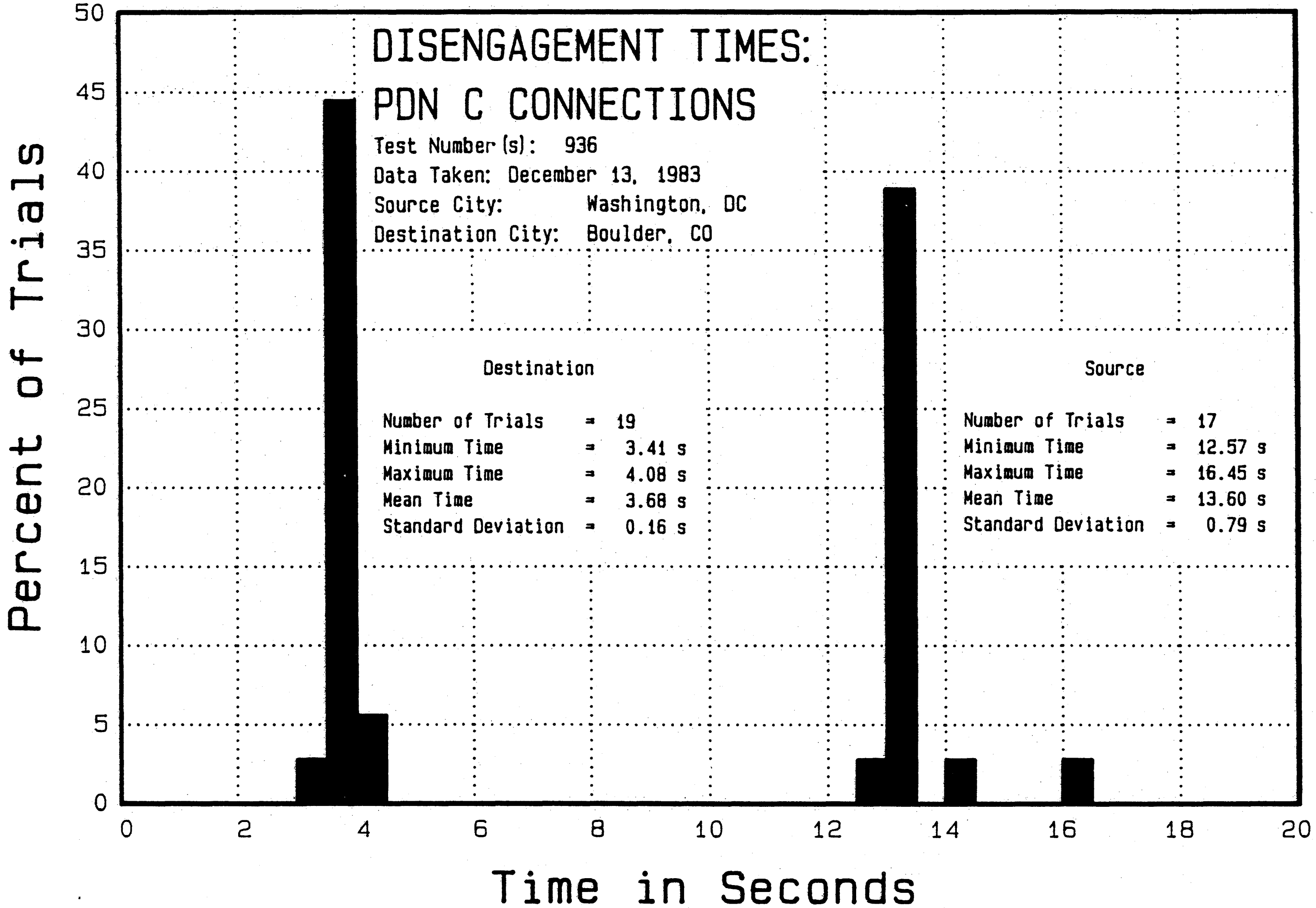


Figure 29. Comparison of source and destination disengagement times.

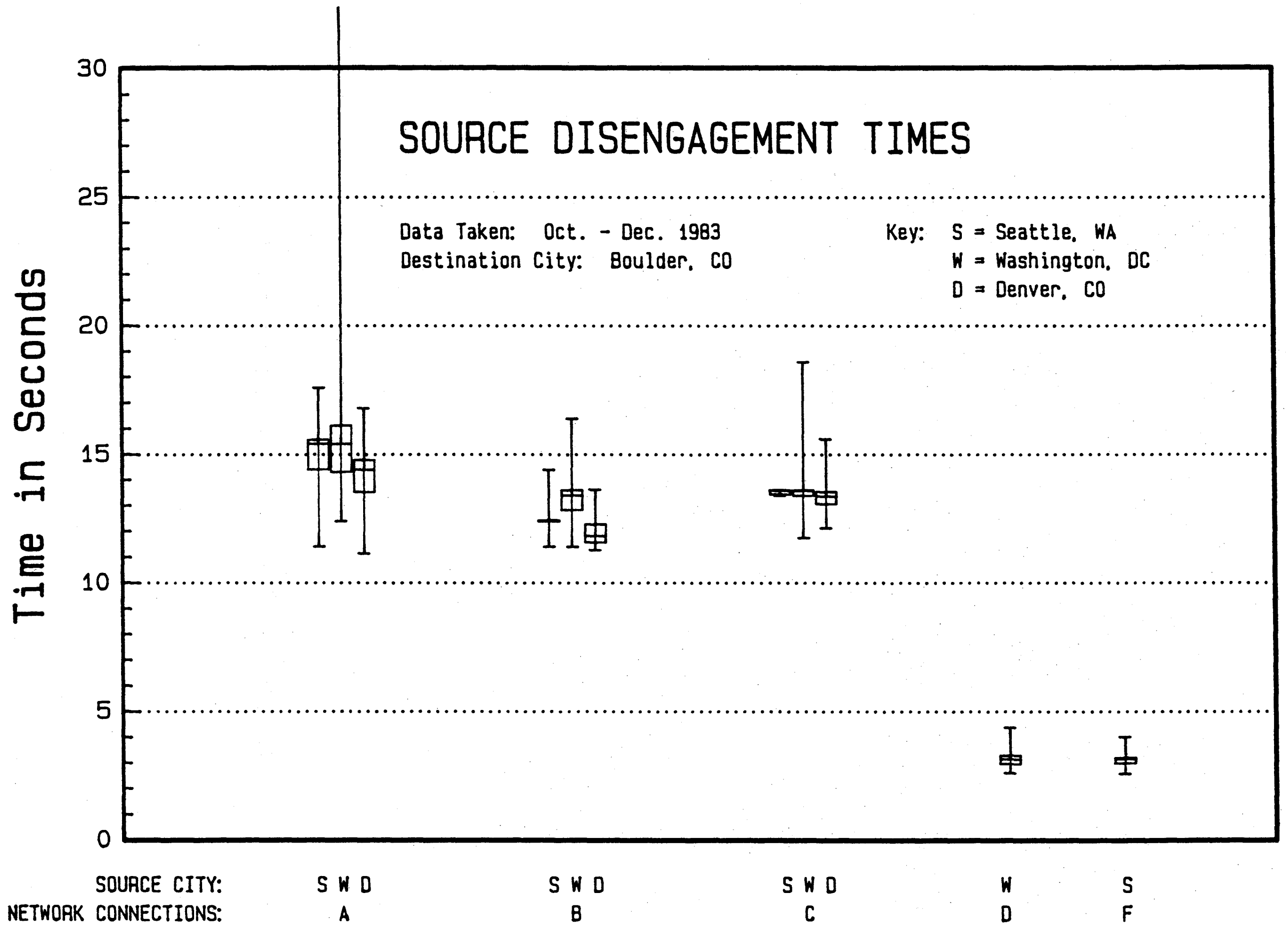
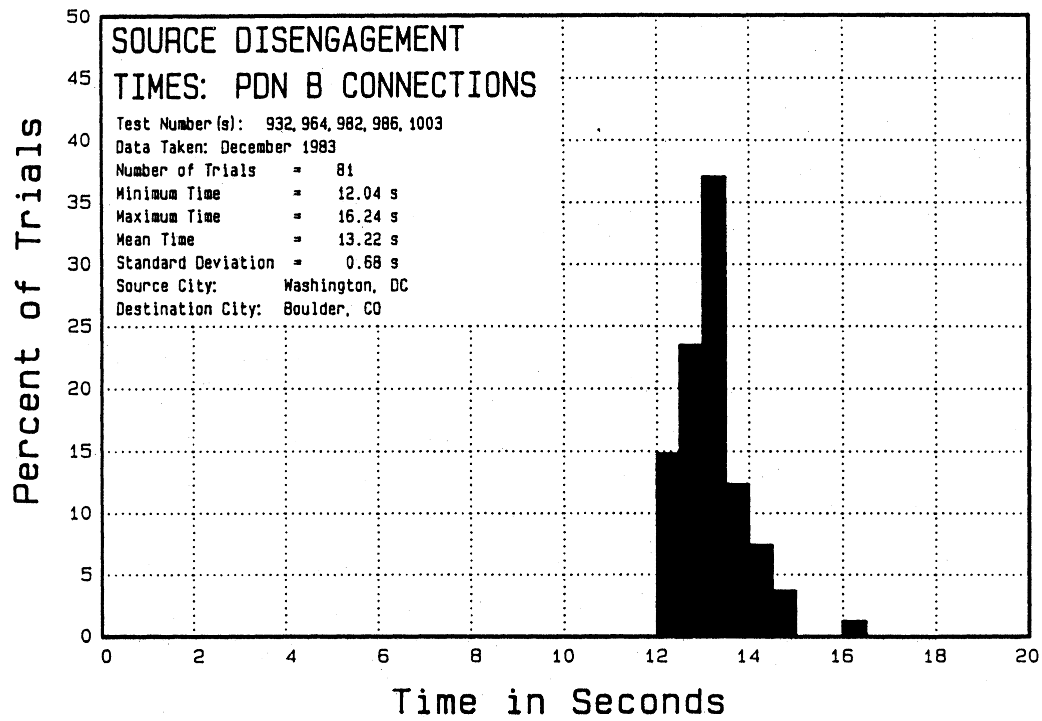
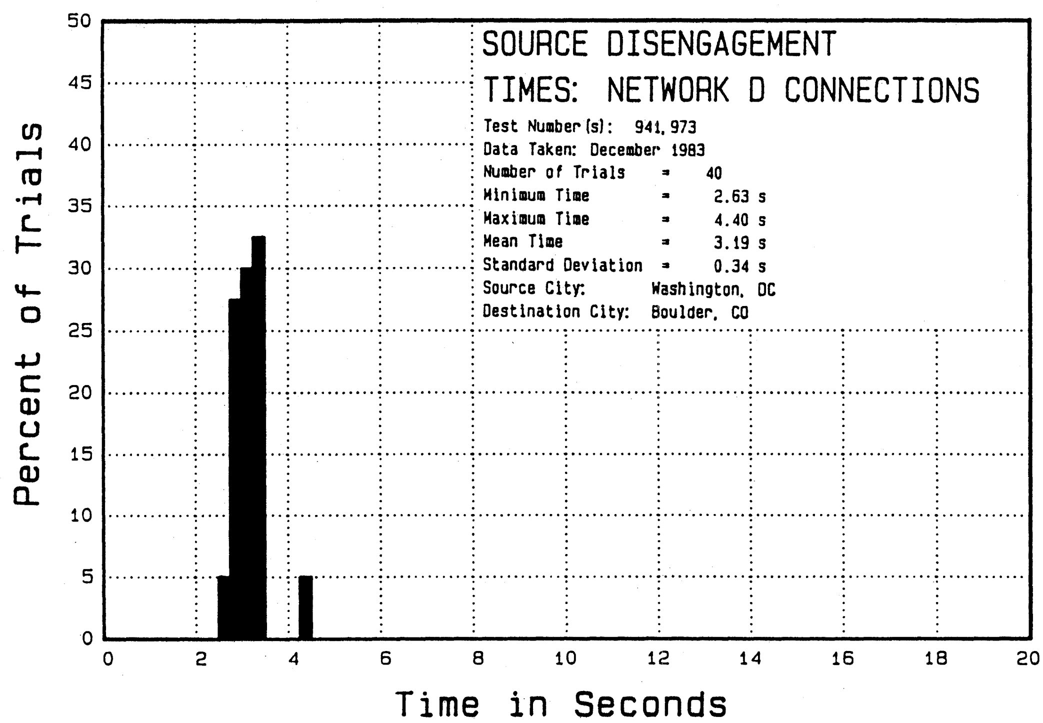


Figure 30. Source disengagement time box plots.



a. Results for PDN B Connections



b. Results for Network D Connections

Figure 31. Comparison of source disengagement times for PDN and PSTN connections.

disengagement times for connections over the telephone networks were a joint result of a less complex disengagement process and shorter transit delays.

Figure 32 shows histograms of overall source disengagement time and its component values for the same set of tests used to construct the histogram in Figure 31a. Host program termination time began with the transmission of the ETX character by XMIT and ended with the subsequent receipt of the UNIX™ operating system prompt issued by the host when execution of the RECV program terminated. This component accounted for 33% of the overall source disengagement time. Host logout time, which began with the issuance of the logout command and ended with the receipt of the host login prompt, accounted for 20% of the overall disengagement time. Local telephone disconnection time began with a request for the modem to enter the command mode and ended with the receipt of a confirmation signal that disconnection was complete; this component accounted for 45% of the total. The remaining 2% of disengagement time (indicated by hachured bars in the figure) was user delay during which the XMIT and RECV programs performed interface monitor functions.

Figure 33 presents chronological plots of source disengagement times for the same tests used to illustrate access time plots in Figure 25. These plots further illustrate that source disengagement times were significantly lower for connections over network D than for connections over the PDNs, and indicate that there was not a strong dependence between successive trials.

Box plots in Figure 34 summarize results of destination disengagement time measurements. As in the source disengagement case, values of destination disengagement time were substantially smaller for connections over the telephone networks than for connections over the PDNs. The plots also reveal distinct differences among the PDN connections.

The total destination disengagement time was the time required to transfer the ETX character from XMIT to RECV, plus the time required for RECV to perform interface monitor functions after receiving the ETX character. A more detailed examination of the data showed that destination disengagement time differences among the PDN connections, and between the PDN connections and the telephone network connections, were mainly associated with differences in the time required to transfer the ETX character. A re-examination of the disengagement data indicated that the ETX transfer time differences also accounted for most of the measured source disengagement time differences among the PDN connections.

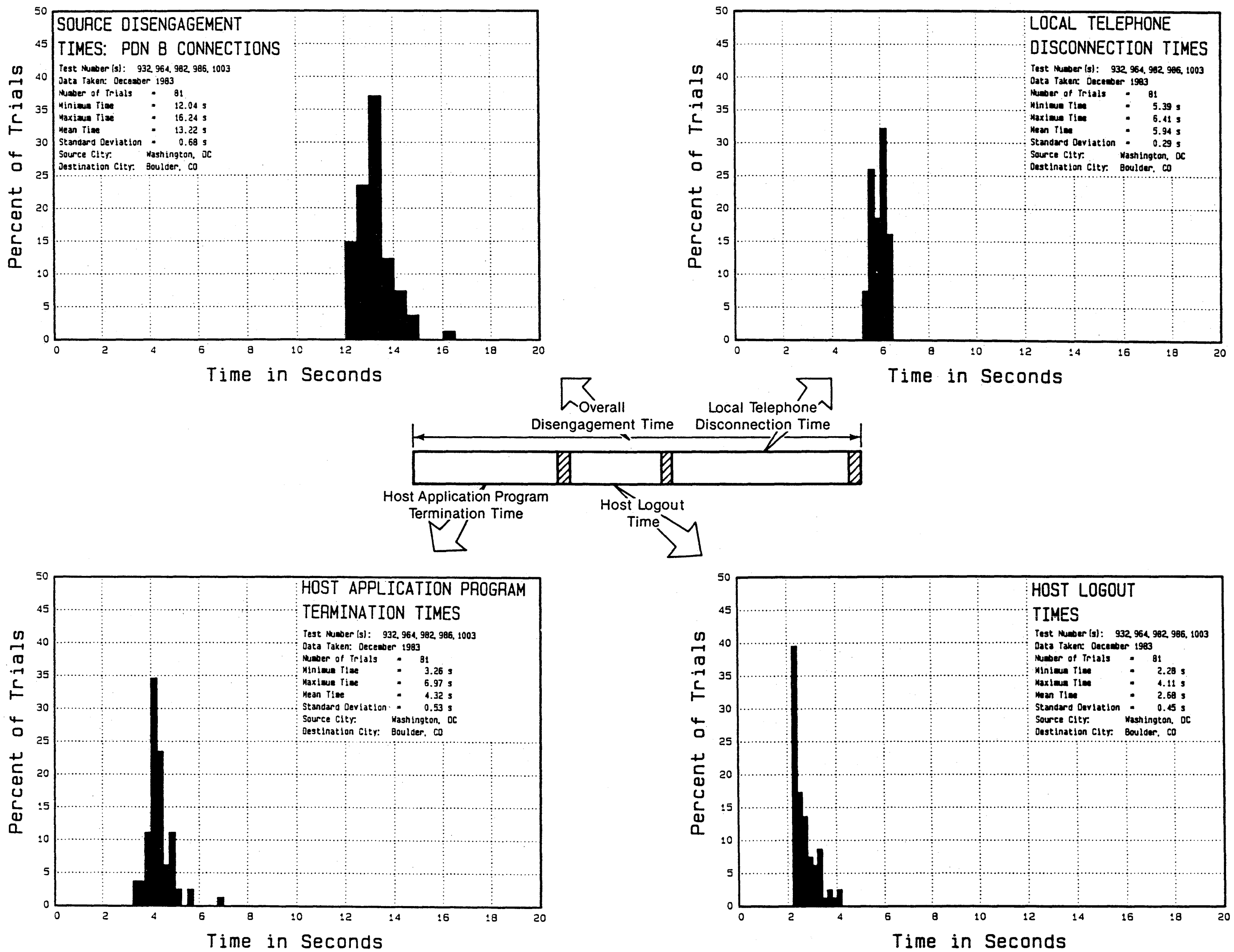
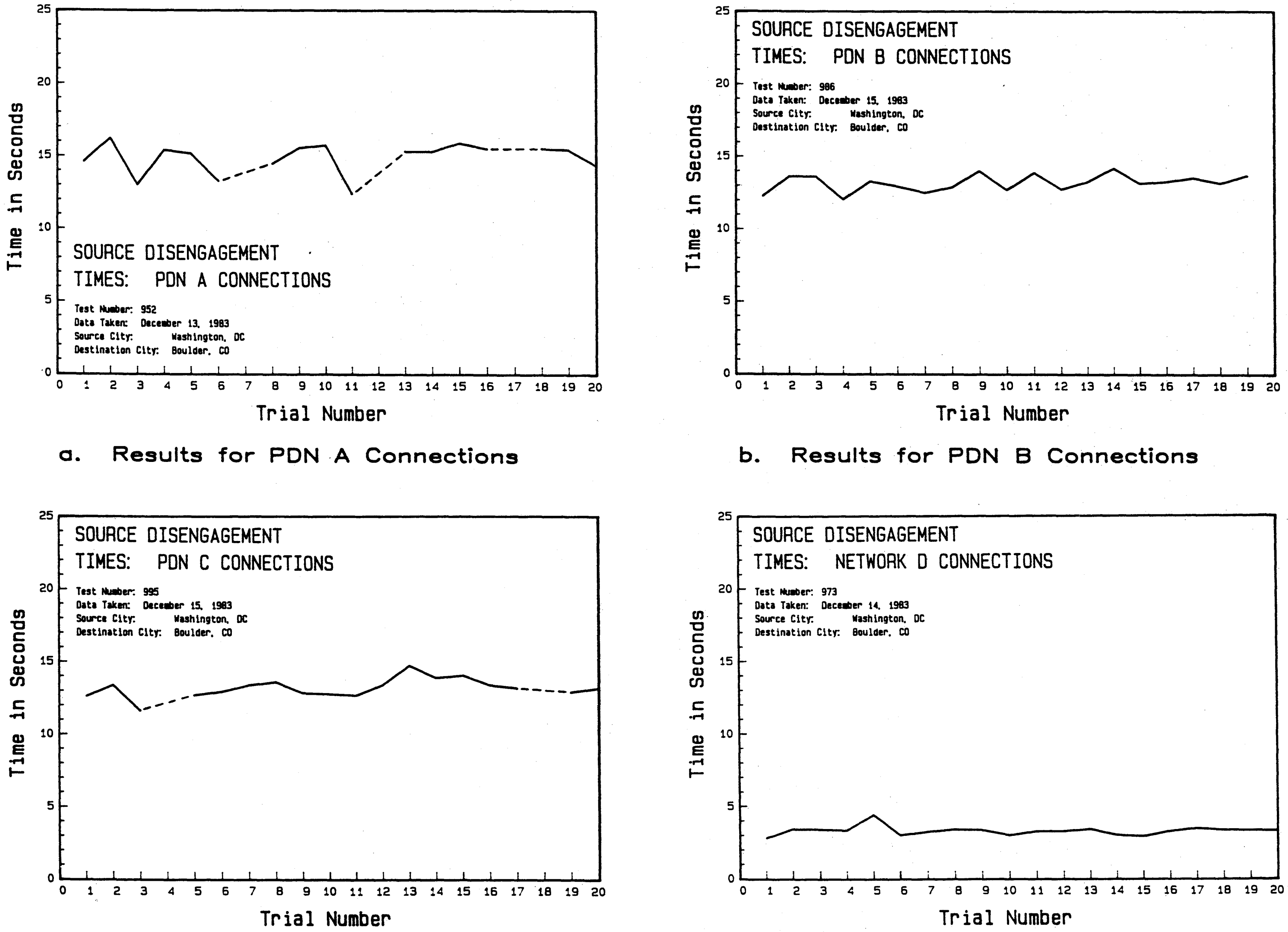


Figure 32. Components of source disengagement time for PDN connections.



a. Results for PDN A Connections

b. Results for PDN B Connections

c. Results for PDN C Connections

d. Results for Network D Connections

Figure 33. Source disengagement time chronological plots.

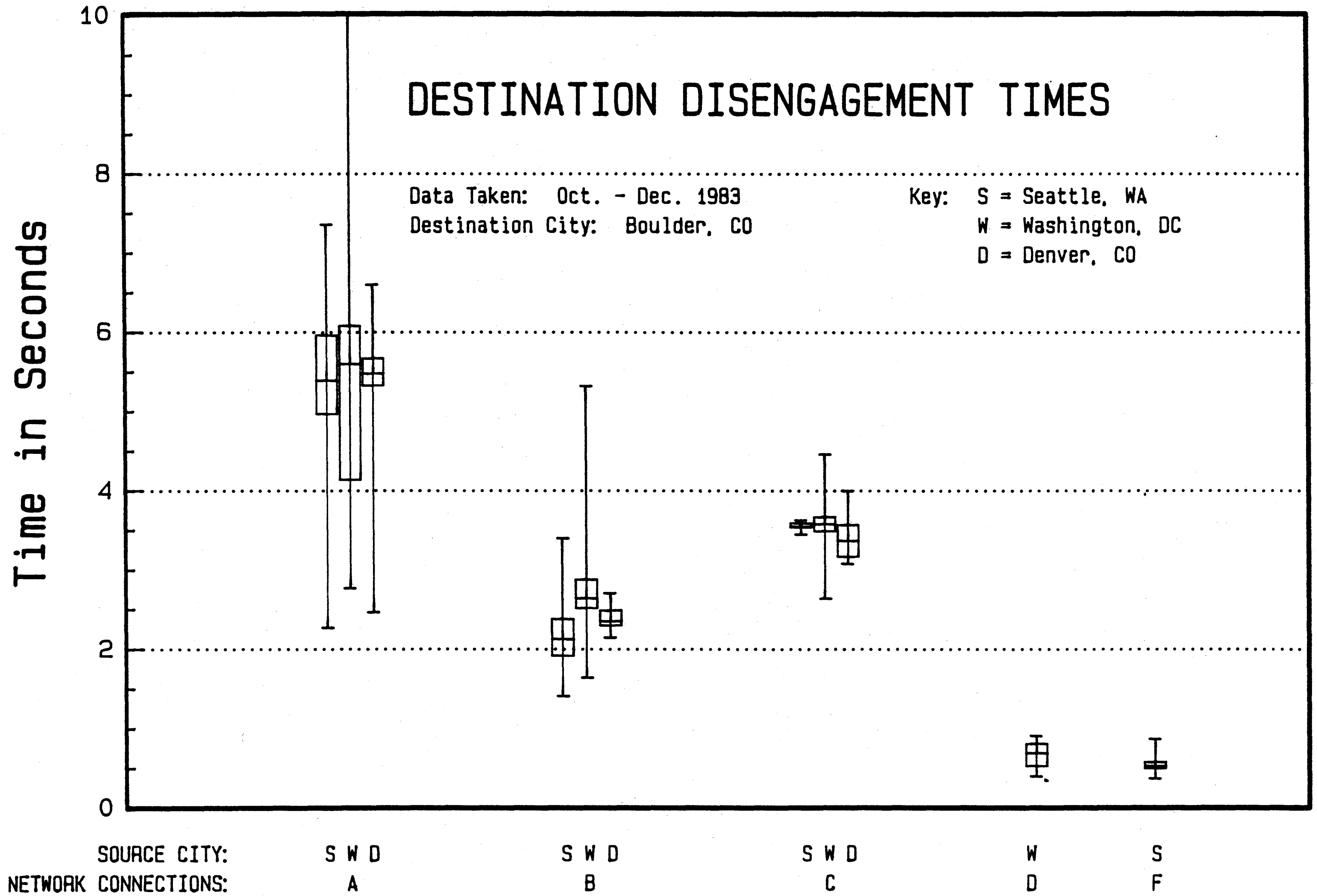


Figure 34. Destination disengagement time box plots.

The histograms of destination disengagement times in Figure 35 are based on the same tests used to construct the histograms of source disengagement times in Figure 31. They further demonstrate that destination disengagement times for connections over network D are significantly shorter and more closely clustered than for connections over PDN B.

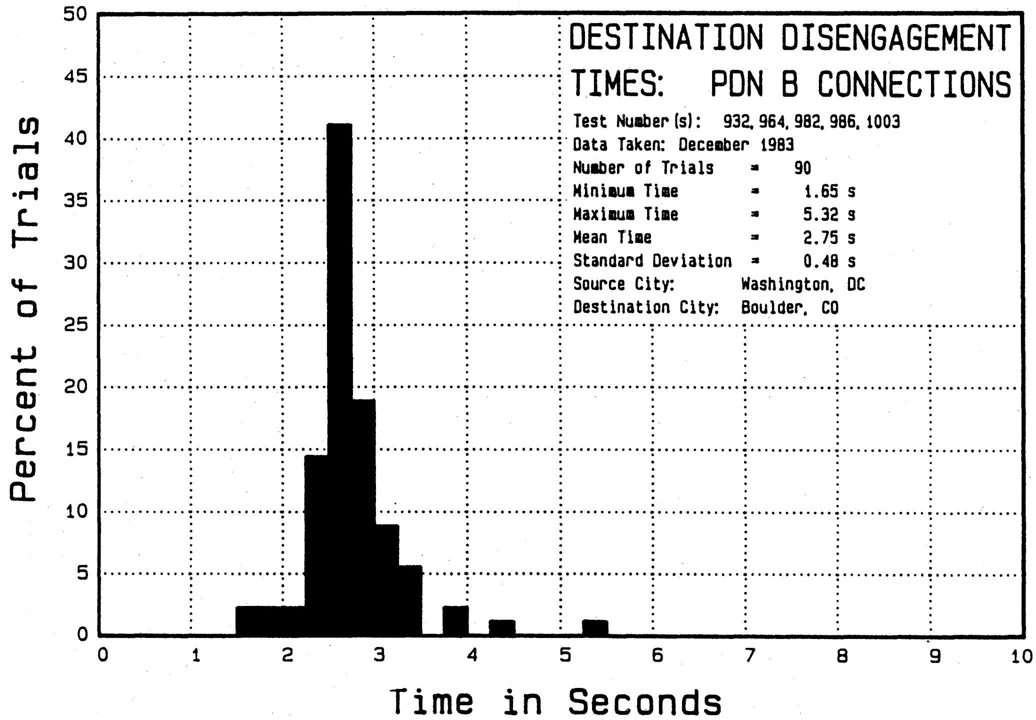
Figure 36 shows chronological plots of destination disengagement times for the same tests used in the access time plots in Figure 25 and in the source disengagement time plots in Figure 33. The chronological plots display some of the same characteristics exhibited by the box plots in Figure 34; i.e., destination disengagement times are longest and most variable for connections over PDN A, and times for connections over network D are significantly shorter and less variable than those for connections over the PDNs.

5.2.7 User Fraction of Disengagement Time

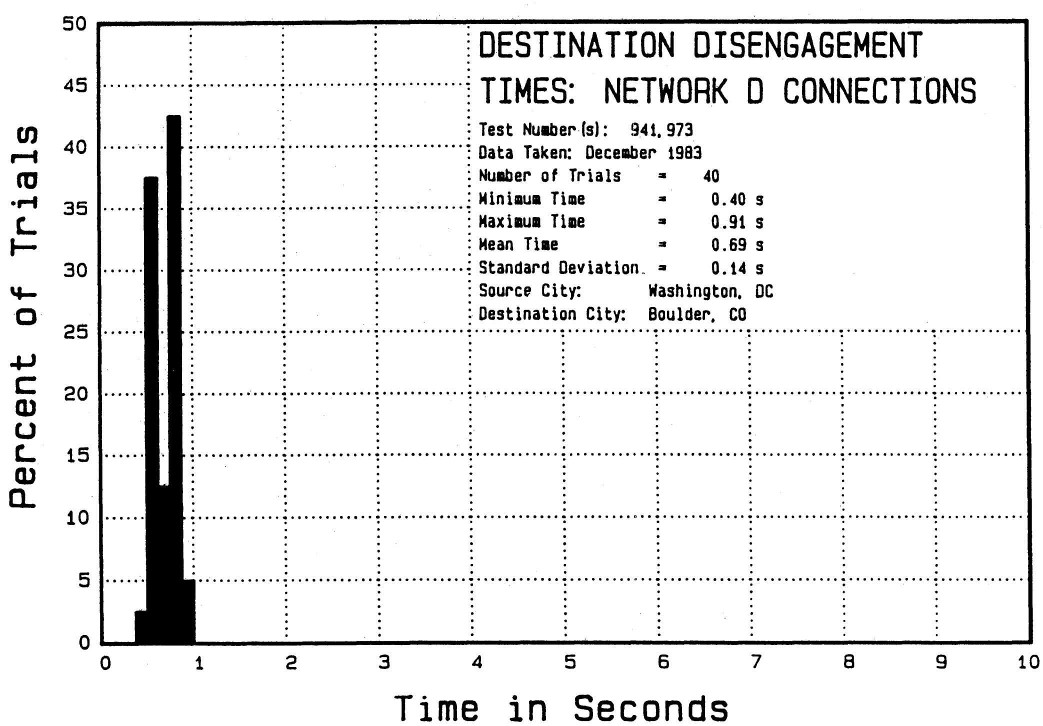
User Fraction of Disengagement Time is the ratio of the average disengagement time for which a user is responsible to the average total performance time for disengagement attempts that result in Successful Disengagement. A disengagement attempt is successful if Disengagement Confirmation occurs within the maximum performance period.

As stated in the previous section, disengagement attempts for source and destination users in the ITS measurements were segregated into separate samples and used to estimate a separate set of disengagement parameter values for each user. Source user disengagement was a negotiated disengagement: the RECV program (the destination user) had to terminate, thereby transmitting a UNIX™ prompt to the source user, before disengagement of the source user could be completed. Both interfaces were therefore relevant in performance time allocation for source user disengagement. Disengagement of the destination user was an independent disengagement, so only the destination interface was relevant in performance time allocation for that function. Because data communication sessions in these measurements were connection oriented, each destination disengagement performance period was a subinterval of the source disengagement period.

User delays associated with the source and destination disengagement functions were produced when the RECV program performed record-keeping at the end of a session (e.g., writing measurement data to the proper files), and when

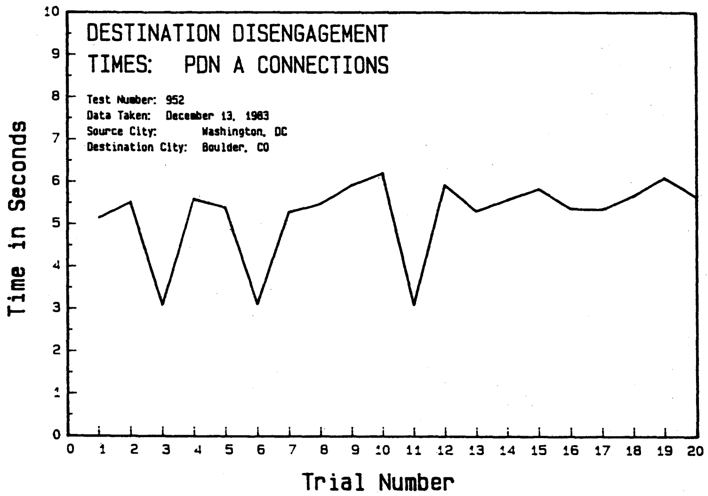


a. Results for PDN B Connections

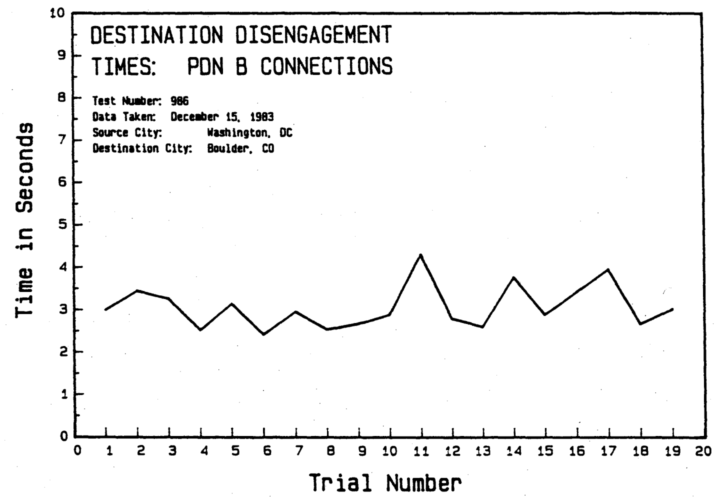


b. Results for Network D Connections

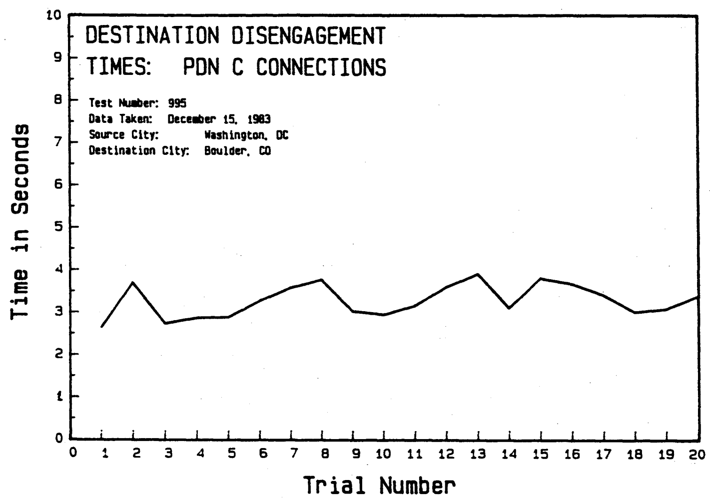
Figure 35. Comparison of destination disengagement times for PDN and PSTN connections.



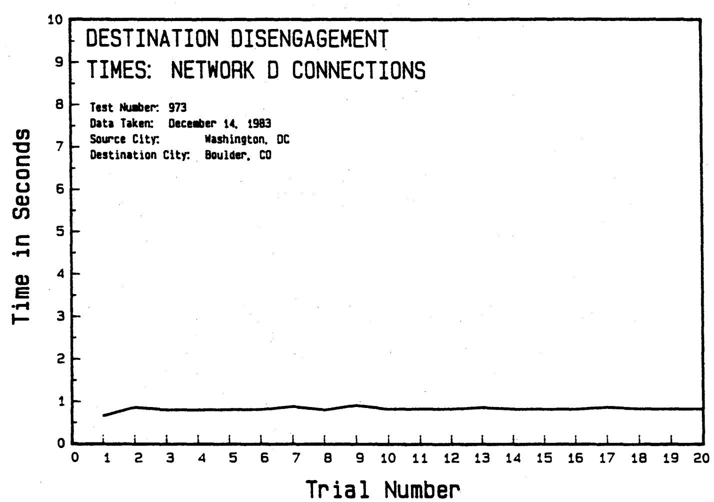
a. **Results for PDN A Connections**



b. **Results for PDN B Connections**



c. **Results for PDN C Connections**



d. **Results for Network D Connections**

Figure 36. Destination disengagement time chronological plots.

the measurement application programs read the satellite clock to obtain times for recorded interface events.

Observed user delays in conducting the disengagement process were largely determined by measurement system characteristics and did not appear to be affected by the performance factors identified in the experiment. Most of the variation in observed values of user delay for individual disengagement attempts was associated with the record-keeping procedures of RECV. Within any test, concluding delays for successive disengagement attempts formed a typical pattern in which the delay for the first attempt was about 0.33 seconds and subsequent delays were substantially longer (most of the latter were 0.57-0.70 seconds, but a few were 0.8-1.2 seconds). Reasons for these variations are not known.

Measured values of User Fraction of Disengagement Time are summarized in Table 13 for several network connection categories. Estimated parameter values and associated information for individual tests are presented in Appendix G.

Table 13. Summary of Measured Values of User Fraction of Disengagement Time

Network Connections	Disengagement Time (seconds)	User Fraction of Disengagement Time
	------------Source------------	
All PDNs	11.7-15.6	0.057-0.079
D/F	2.9-4.1	0.23-0.27
	----------Destination----------	
PDN A	4.8-5.9	0.12-0.16
PDN B	2.0-3.1	0.21-0.35
PDN C	3.3-3.7	0.16-0.21
D/F	0.52-0.94	0.76-0.92

Most of the observed user delay for disengagement was a result of interface monitor functions performed by the XMIT and RECV application programs and would not have occurred otherwise. Consequently, measured values of User Fraction of Disengagement Time obtained in the ITS measurements did not represent typical operating conditions. They did, however, accurately account for the influence of the measurement system on observed values of Disengagement Time.

5.2.8 Disengagement Denial Probability

Disengagement Denial occurs if a disengagement attempt is not completed during the maximum performance period and the system is responsible for the failure. Disengagement Denial Probability is the (conditional) probability that Disengagement Denial occurs in a disengagement attempt that does not result in User Disengagement Blocking. In a performance measurement, this probability is estimated by the ratio of the number of Disengagement Denial outcomes to the total number of disengagement attempts in the measurement sample.

Source Disengagement Denial outcomes are shown by $d1_{\ell}$ in Table 11. Estimated values of source Disengagement Denial Probability are plotted in Figure 37 for each of the 51 access-disengagement tests. There were no obvious differences among the PDN connections, but no instances of source Disengagement Denial were observed in tests on connections over either of the telephone networks.

Destination Disengagement Denial outcomes are shown by $d2_{\ell}$ in Table 11. Only two instances of destination Disengagement Denial were observed in the disengagement measurements. Both occurred in a single test (928) on connections over a PDN A, and were the result of the loss of the ETX character. In each instance, several characters at the end of the associated user information block were also lost. (Flow control was not enabled in this test.) After a prescribed delay during which no characters were received, RECV timed out, then performed some record-keeping and returned control to the host operating system. The termination of execution corresponded to the end of disengagement for the destination user (the RECV program), but it occurred after the end of the maximum performance period. The system was in the responsible state at the destination interface during the inactive interval that preceded disengagement timeout, and the measured user fraction of performance time for the unsuccessful attempt was less than the specified value of User Fraction of Disengagement Time. Hence, the system was assigned responsibility for the failure and the outcome was Disengagement Denial. The delay resulting from data loss also produced abnormally large values of source disengagement time, but they did not exceed the maximum performance time.

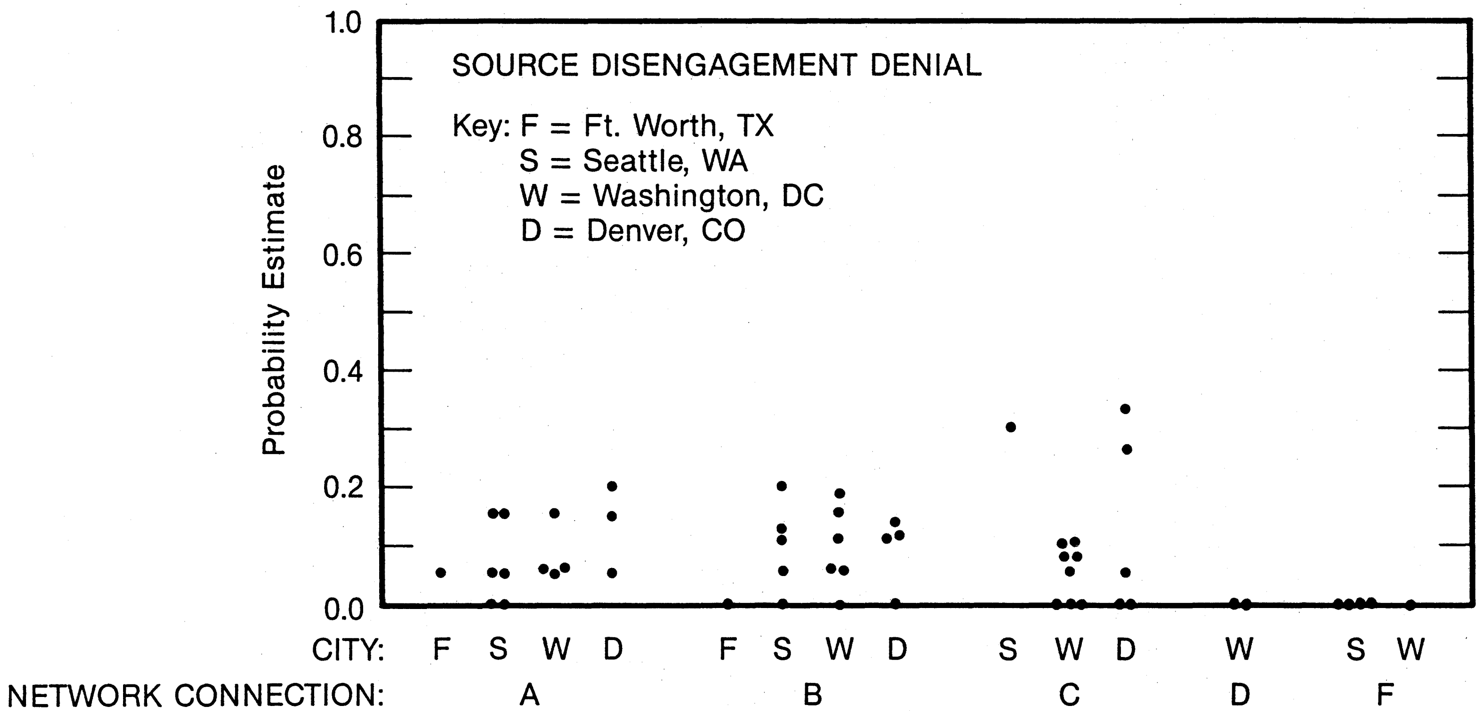


Figure 37. Source disengagement denial probability plots.

5.3 User Information Transfer Performance

Results described in this section are based on the 214 user information transfer tests listed in Table 14. This table groups tests according to block size and shows factor levels for each test. Except for the utilization level (column 7), factor level listings were explained in Section 5.2. Low utilization (indicated by u-lo) included an additional 1-second delay between the input of successive user information blocks, whereas high utilization (indicated by u-hi) omitted this delay. Although flow control and utilization were not included in the design of the experiment, they had a major effect on certain user information transfer parameters. The applicable levels of these two factors are summarized in Table 15 for each network connection and source city. Except for the two misdelivery probabilities, values were measured for all user information transfer parameters defined in ANS X3.102. Results for each measured parameter are described in the subsections that follow.

5.3.1 Block Transfer Time

Block Transfer Time is the average value of the duration of a successful block transfer attempt. A block transfer attempt is successful if

- o the transmitted block is delivered to the intended destination user within the maximum performance period and
- o the contents of the delivered block are correct.

The box plots in Figure 38 summarize all measured values of block transfer time. Results for 64-, 128-, and 512-character blocks are presented in separate diagrams. Within a given diagram, each box plot represents data for connections over a particular network, a particular source city, and a particular utilization level. The plots are clustered according to network connections. Utilization levels are indicated in each diagram; note that both low- and high-utilization results are available only for transfer from Washington, DC.

The plots clearly show that block transfer delays were shorter and generally less variable for connections over the telephone networks D and F than for connections over the PDNs. The effect of utilization levels can be observed by comparing, in each network cluster, the right-hand pair of box plots (corresponding to high utilization) with the box plots to their left (corresponding to low utilization). Block transfer times for high utilization were generally longer and more variable than those for low utilization.

Table 14. User Information Transfer Tests Used in Data Analysis

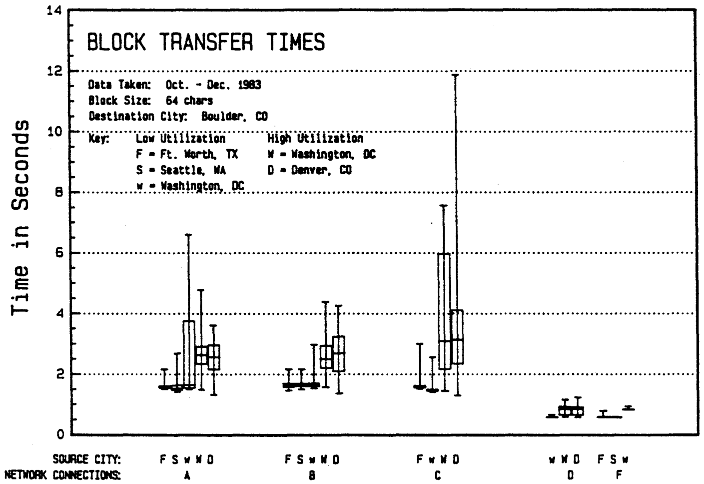
Test	Test Conditions
682	ftw B mon 3 S u-lo f-on tone
697	ftw B tue 2 S u-lo f-on tone
703	ftw C tue 3 S u-lo foff tone
712	ftw F tue 3 S u-lo foff tone
715	ftw A tue 4 S u-lo foff tone
723	ftw A wed 3 S u-lo foff tone
726	ftw F wed 4 S u-lo foff tone
740	ftw F thu 1 S u-lo foff tone
741	ftw C thu 1 S u-lo foff tone
748	ftw A thu 2 S u-lo foff tone
750	ftw B thu 3 S u-lo f-on tone
760	ftw C thu 4 S u-lo foff tone
774	ftw A fri 1 S u-lo foff tone
776	ftw B fri 2 S u-lo f-on tone
788	sea B thu 1 S u-lo f-on tone
799	sea F thu 3 S u-lo foff tone
804	sea B thu 4 S u-lo f-on tone
810	sea A thu 5 S u-lo foff tone
814	sea A fri 6 S u-lo foff tone
818	sea F fri 1 S u-lo foff tone
822	sea A fri 2 S u-lo foff tone
829	sea B mon 2 S u-lo f-on tone
833	sea A mon 3 S u-lo foff tone
836	sea F mon 4 S u-lo foff tone
847	sea B wed 5 S u-lo f-on tone
853	sea B thu 6 S u-lo f-on tone
855	sea A thu 1 S u-lo foff tone
861	sea F thu 2 S u-lo foff tone
866	sea B thu 3 S u-lo f-on tone
875	sea A thu 4 S u-lo foff tone
877	sea F thu 5 S u-lo foff tone
888	wdc C sun 5 S u-lo f-on puls
894	wdc C mon 6 S u-lo f-on puls
897	wdc F mon 1 S u-lo foff puls
898	wdc F mon 1 S u-lo foff puls
900	wdc A mon 2 S u-lo foff puls
906	wdc B mon 3 S u-lo f-on tone
910	wdc C mon 4 S u-lo f-on tone
916	wdc C mon 5 S u-lo f-on tone
922	wdc D tue 6 S u-lo foff tone
924	wdc A tue 1 S u-lo foff tone
930	wdc B tue 2 S u-lo f-on tone
935	wdc C tue 3 S u-lo f-on tone
938	wdc D tue 4 S u-lo foff tone
949	wdc A tue 5 S u-hi f-on tone
958	wdc B wed 1 S u-hi f-on tone
968	wdc C wed 2 S u-hi f-on tone
972	wdc D wed 3 S u-hi foff tone
975	wdc A wed 4 S u-hi f-on tone
979	wdc B wed 5 S u-hi f-on tone
985	wdc B thu 6 S u-hi f-on tone
991	wdc D thu 2 S u-hi foff tone
996	wdc A thu 3 S u-hi f-on tone
999	wdc A thu 3 S u-hi f-on tone
1001	wdc B thu 4 S u-hi f-on tone
1005	wdc C thu 5 S u-hi f-on tone
1011	den C tue 5 S u-hi f-on puls
1017	den C wed 6 S u-hi f-on puls
1020	den D wed 1 S u-hi foff puls
1024	den A wed 2 S u-hi f-on puls
1030	den B wed 3 S u-hi f-on puls
1032	den C wed 4 S u-hi f-on puls
1042	den D thu 6 S u-hi foff puls
1044	den B thu 1 S u-hi f-on puls
1051	den C thu 2 S u-hi f-on puls
1061	den A thu 4 S u-hi f-on puls
1063	den A thu 5 S u-hi f-on puls
1069	den B fri 6 S u-hi f-on puls
1074	den C fri 1 S u-hi f-on puls
1076	den A fri 2 S u-hi f-on puls
1082	den B fri 2 S u-hi f-on puls

Test	Test Conditions
683	ftw B mon 3 M u-lo f-on tone
685	ftw C mon 4 M u-lo foff tone
699	ftw B tue 2 M u-lo f-on tone
701	ftw C tue 3 M u-lo foff tone
711	ftw F tue 3 M u-lo foff tone
716	ftw A tue 4 M u-lo foff tone
724	ftw A wed 3 M u-lo foff tone
737	ftw F thu 1 M u-lo foff tone
746	ftw A thu 2 M u-lo foff tone
752	ftw B thu 3 M u-lo f-on tone
754	ftw A thu 4 M u-lo foff tone
755	ftw C thu 4 M u-lo foff tone
757	ftw D thu 4 M u-lo foff tone
758	ftw F thu 4 M u-lo foff tone
771	ftw A fri 1 M u-lo foff tone
778	ftw B fri 2 M u-lo f-on tone
789	sea B thu 1 M u-lo f-on tone
798	sea F thu 3 M u-lo foff tone
803	sea B thu 4 M u-lo f-on tone
809	sea A thu 5 M u-lo foff tone
813	sea A fri 6 M u-lo foff tone
817	sea F fri 1 M u-lo foff tone
820	sea A fri 2 M u-lo foff tone
824	sea C mon 1 M u-lo foff tone
830	sea B mon 2 M u-lo f-on tone
832	sea A mon 3 M u-lo foff tone
838	sea F mon 4 M u-lo foff tone
848	sea B wed 5 M u-lo f-on tone
852	sea B thu 6 M u-lo f-on tone
856	sea A thu 1 M u-lo foff tone
860	sea F thu 2 M u-lo foff tone
864	sea B thu 3 M u-lo f-on tone
873	sea A thu 4 M u-lo foff tone
887	wdc C sun 4 M u-lo f-on puls
889	wdc C sun 5 M u-lo f-on puls
893	wdc C mon 6 M u-lo f-on puls
902	wdc A mon 2 M u-lo foff puls
904	wdc B mon 3 M u-lo f-on tone
909	wdc C mon 4 M u-lo f-on tone
921	wdc D tue 6 M u-lo foff tone
925	wdc A tue 1 M u-lo foff tone
931	wdc B tue 2 M u-lo f-on tone
933	wdc C tue 3 M u-lo f-on tone
940	wdc D tue 4 M u-lo foff tone
950	wdc A tue 5 M u-hi f-on tone
959	wdc B wed 1 M u-hi f-on tone
971	wdc D wed 3 M u-hi foff tone
976	wdc A wed 4 M u-hi f-on tone
980	wdc B wed 5 M u-hi f-on tone
984	wdc B thu 6 M u-hi f-on tone
988	wdc C thu 1 M u-hi f-on tone
993	wdc D thu 2 M u-hi foff tone
998	wdc A thu 3 M u-hi f-on tone
1002	wdc B thu 4 M u-hi f-on tone
1006	wdc C thu 5 M u-hi f-on tone
1009	den D tue 4 M u-hi foff puls
1012	den C tue 5 M u-hi f-on puls
1016	den C wed 6 M u-hi f-on puls
1025	den A wed 2 M u-hi f-on puls
1029	den B wed 3 M u-hi f-on puls
1033	den C wed 4 M u-hi f-on puls
1041	den D thu 6 M u-hi foff puls
1045	den B thu 1 M u-hi f-on puls
1052	den C thu 2 M u-hi f-on puls
1060	den A thu 4 M u-hi f-on puls
1064	den A thu 5 M u-hi f-on puls
1072	den C fri 1 M u-hi f-on puls
1077	den A fri 2 M u-hi f-on puls
1081	den B fri 2 M u-hi f-on puls

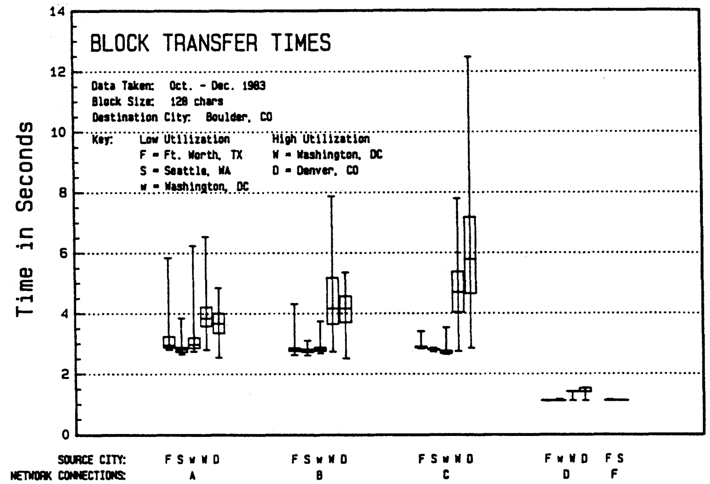
Test	Test Conditions
680	ftw A mon 3 L u-lo foff tone
681	ftw B mon 3 L u-lo f-on tone
698	ftw B tue 2 L u-lo f-on tone
705	ftw C tue 3 L u-lo foff tone
709	ftw F tue 3 L u-lo foff tone
718	ftw A tue 4 L u-lo foff tone
721	ftw B wed 2 L u-lo f-on tone
722	ftw A wed 3 L u-lo foff tone
727	ftw F wed 4 L u-lo foff tone
739	ftw F thu 1 L u-lo foff tone
743	ftw C thu 1 L u-lo foff tone
747	ftw A thu 2 L u-lo foff tone
751	ftw B thu 3 L u-lo f-on tone
759	ftw C thu 4 L u-lo foff tone
773	ftw A fri 1 L u-lo foff tone
777	ftw B fri 2 L u-lo f-on tone
787	sea B thu 1 L u-lo f-on tone
797	sea F thu 3 L u-lo foff tone
805	sea B thu 4 L u-lo f-on tone
808	sea A thu 5 L u-lo foff tone
812	sea A fri 6 L u-lo foff tone
816	sea F fri 1 L u-lo foff tone
821	sea A fri 2 L u-lo foff tone
826	sea C mon 1 L u-lo foff tone
828	sea B mon 2 L u-lo f-on tone
834	sea A mon 3 L u-lo foff tone
837	sea F mon 4 L u-lo foff tone
849	sea B wed 5 L u-lo f-on tone
851	sea B thu 6 L u-lo f-on tone
857	sea A thu 1 L u-lo foff tone
859	sea F thu 2 L u-lo foff tone
865	sea B thu 3 L u-lo f-on tone
874	sea A thu 4 L u-lo foff tone
890	wdc C sun 5 L u-lo f-on puls
892	wdc C mon 6 L u-lo f-on puls
896	wdc F mon 1 L u-lo foff puls
901	wdc A mon 2 L u-lo foff puls
905	wdc B mon 3 L u-lo f-on tone
911	wdc C mon 4 L u-lo f-on tone
914	wdc C mon 4 L u-lo f-on tone
918	wdc C mon 5 L u-lo f-on tone
920	wdc D tue 6 L u-lo foff tone
926	wdc A tue 1 L u-lo foff tone
929	wdc B tue 2 L u-lo f-on tone
934	wdc C tue 3 L u-lo f-on tone
939	wdc D tue 4 L u-lo foff tone
951	wdc A tue 5 L u-hi f-on tone
953	wdc A wed 6 L u-hi f-on tone
960	wdc B wed 1 L u-hi f-on tone
967	wdc C wed 2 L u-hi f-on tone
970	wdc D wed 3 L u-hi foff tone
977	wdc A wed 4 L u-hi f-on tone
981	wdc B wed 5 L u-hi f-on tone
983	wdc B thu 6 L u-hi f-on tone
987	wdc C thu 1 L u-hi f-on tone
992	wdc D thu 2 L u-hi foff tone
1000	wdc B thu 4 L u-hi f-on tone
1004	wdc A thu 4 L u-hi f-on tone
1007	wdc C thu 5 L u-hi f-on tone
1010	den B tue 4 L u-hi f-on puls
1015	den C wed 6 L u-hi f-on puls
1019	den D wed 1 L u-hi foff puls
1026	den A wed 2 L u-hi f-on puls
1028	den B wed 3 L u-hi f-on puls
1034	den C wed 4 L u-hi f-on puls
1040	den D thu 6 L u-hi foff puls
1046	den B thu 1 L u-hi f-on puls
1049	den C thu 2 L u-hi f-on puls
1059	den A thu 4 L u-hi f-on puls
1065	den A thu 5 L u-hi f-on puls
1067	den B fri 6 L u-hi f-on puls
1071	den C fri 1 L u-hi f-on puls
1078	den A fri 2 L u-hi f-on puls
1080	den B fri 2 L u-hi f-on puls

Table 15. Flow Control and Utilization Levels in User Information Transfer Tests

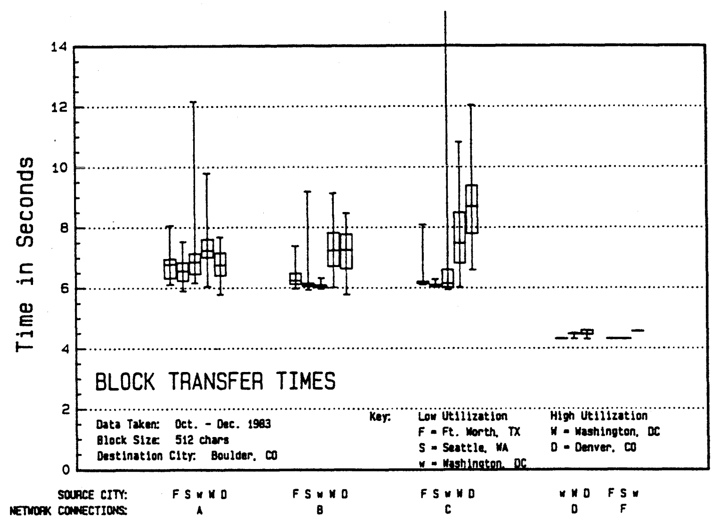
SOURCE CITY	PDN A		PDN B		PDN C		NETWORK D		NETWORK F	
	FLOW CONTROL	UTILIZATION	FLOW CONTROL	UTILIZATION	FLOW CONTROL	UTILIZATION	FLOW CONTROL	UTILIZATION	FLOW CONTROL	UTILIZATION
Fort Worth, TX	off	low	on	low	off	low	—	—	off	low
Seattle, WA	off	low	on	low	off	low	—	—	off	low
Washington, DC (888-941)	off	low	on	low	on	low	off	low	off	low
Washington, DC (949-1008)	on	high	on	high	on	high	off	high	—	—
Denver, CO	on	high	on	high	on	high	off	high	—	—



a. Short (64—character) Blocks



b. Medium (128—character) Blocks



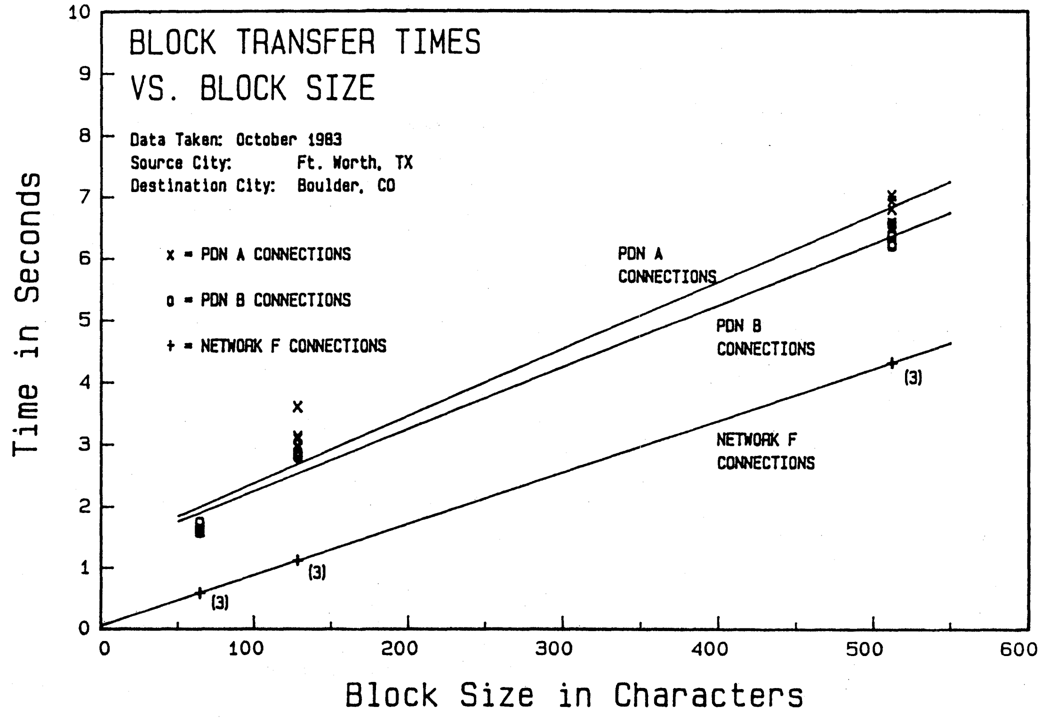
c. Long (512—character) Blocks

Figure 38. Block transfer time box plots.

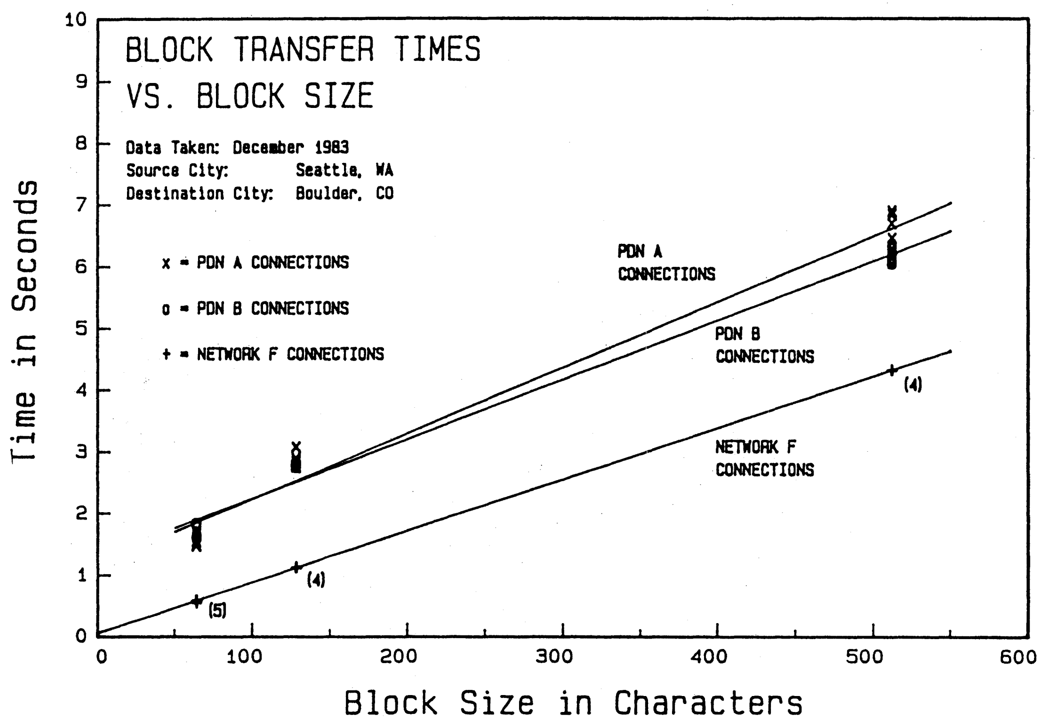
Surprisingly, the largest median delays for connections over PDN C usually occurred in tests from Denver, which traversed the shortest physical path. A possible explanation is that a bottleneck may have existed in the Denver node, such as a low-capacity switch that handled locally generated traffic, but not transit traffic. Median delay tended to increase as block length increased.

Block length effects are shown more clearly in Figure 39, where Block Transfer Time for connections over PDNs A and B and network F (FTS) is plotted as a function of block length. The data represent measurements made at low utilization for transfer from two different remote sites: Fort Worth, TX (Figure 39a), and Seattle, WA (Figure 39b). For PDN connections, each data point represents the results of a single test. For network F connections, each data point represents the results of several tests whose values coincided; the number of tests represented is indicated in parentheses beside the point. For connections over network F, measured block transfer times were nearly equal to transmission times determined by the access line speed of 120 characters/second. Measured block transfer times for connections over the PDNs were substantially longer because of store-and-forward delays in the PDN switches. Regression lines were fitted by the method of least squares to measured data for connections over each of the indicated networks. As expected, the relationship between Block Transfer Time and block size is very nearly linear for connections over network F, whereas the relationship is only roughly linear for connections over the PDNs. For the latter, a likely source of nonlinearity is the splitting of large user information blocks into multiple packets. A more accurate representation of the relationship between transfer time and block size for connections over the PDNs would require measurements at several intermediate block sizes.

Figure 40 presents typical histograms of block transfer times for connections over the PDNs and Network D. Each histogram represents a single test that transferred 128-character blocks from Washington, DC, under high utilization conditions. The histograms show substantially longer delays and more variability for PDN connections than for network D connections. The mean value for transfer via the three PDNs was 4.40 seconds, compared with 1.41 seconds for transfer via network D. Another significant observation is that the delay distributions for connections over PDN A and PDN B are clearly skewed to the right, suggesting a gamma or lognormal distribution, whereas the distribution for connections over PDN C appears nearly uniform. These results

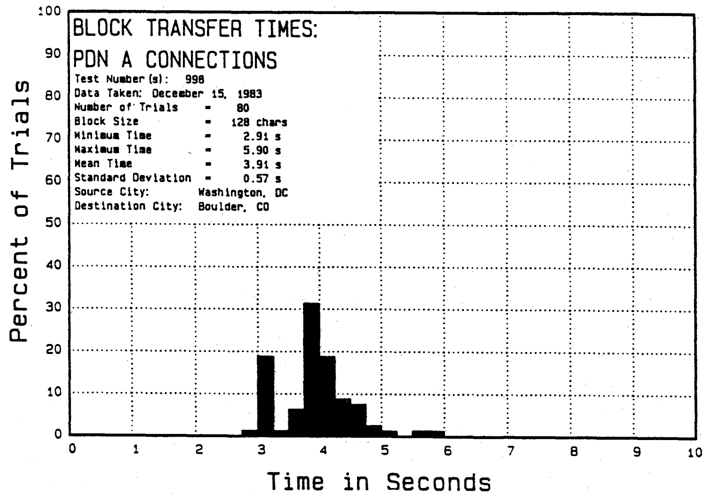


a. Ft. Worth, TX Results

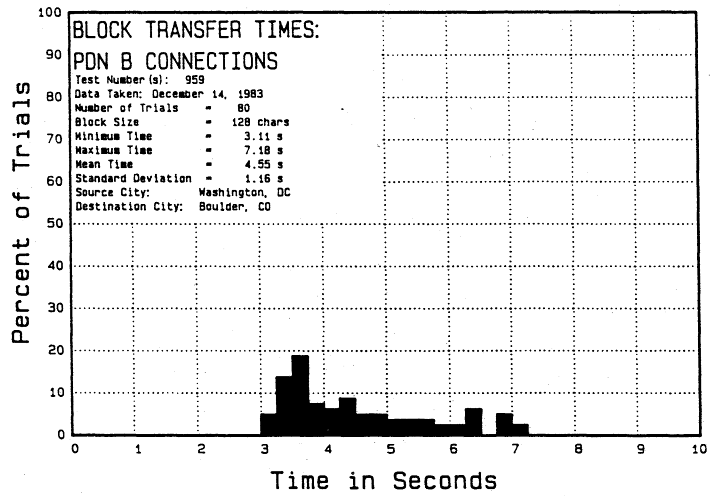


b. Seattle, WA Results

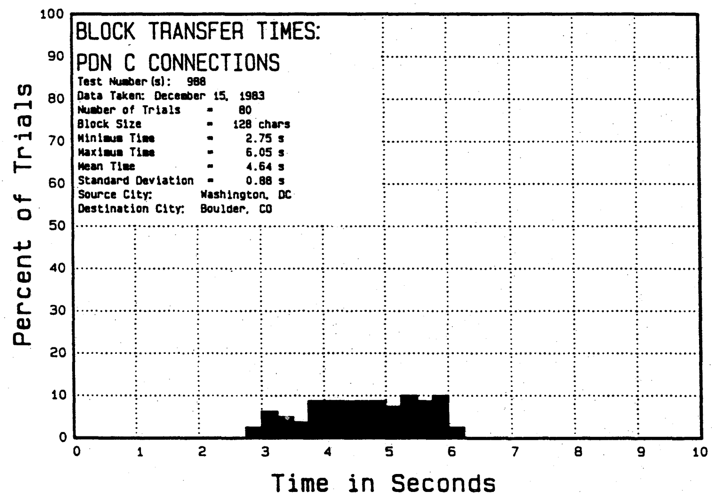
Figure 39. Block transfer time regression plots.



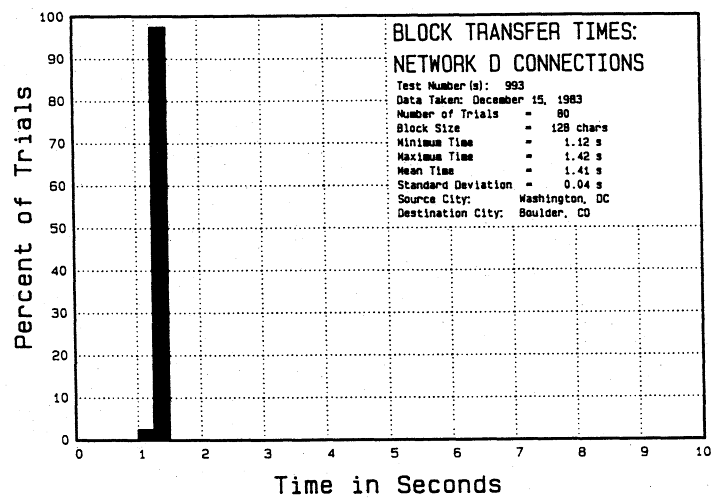
a. Results for PDN A Connections



b. Results for PDN B Connections



c. Results for PDN C Connections



d. Results for Network D Connections

Figure 40. Block transfer time histograms for Washington, DC.

are typical for the high-utilization tests. As expected, there was essentially no variability in block transfer times for connections over Network D. Figure 41 shows block transfer time histograms for similar tests from Denver. The delay distribution for transfer via PDN C again appears nearly uniform, but skewing in the distributions for transfer via PDN A or PDN B is not significant.

Figures 42a and 42b show chronological plots of block transfer times for the same high-utilization tests used to construct the histograms in Figures 40 and 41, respectively. Transfer times for connections over Network D were essentially constant, whereas those for connections over the PDNs exhibited distinctive patterns of variation.

Despite obvious differences in the overall appearance of the patterns, certain features occurred in all patterns. The most prominent of these were intervals in which there was an essentially uniform increase in block transfer time from one trial to the next. Moreover, the rate of this "steady" increase (the local slope of the plot) was nearly the same for each pattern, regardless of the PDN used or the source city. The source and destination event histories showed that the "steady" increase in block transfer time was the joint result of an almost uniform block input rate and an almost uniform but slightly lower block output rate. The "steady" input rate corresponded very closely to the 1200 bps transmission rate from the source computer to the PDN (each transmitted ASCII character included a start bit and a stop bit in addition to the standard 8-bit representation, and each block included a carriage return in addition to the 128 characters of user information). However, reasons why the "steady" block output rate was lower and independent of the network connection are not understood.

Exceptions to the "steady" or "normal" increase of block transfer time occurred as abrupt and abnormally large increases in transfer time or as abrupt decreases in transfer time. An examination of event times showed that each abnormal increase in block transfer time was associated with an abnormally long delay between the output of the affected block and the output of the preceding block. The examination also showed that each decrease in block transfer time was associated with an abnormally long delay between the input of the affected block and the input of the preceding block.

An abnormally long delay between the input of two successive blocks occurred when the WRITE COMPLETE response to a WRITE command was abnormally

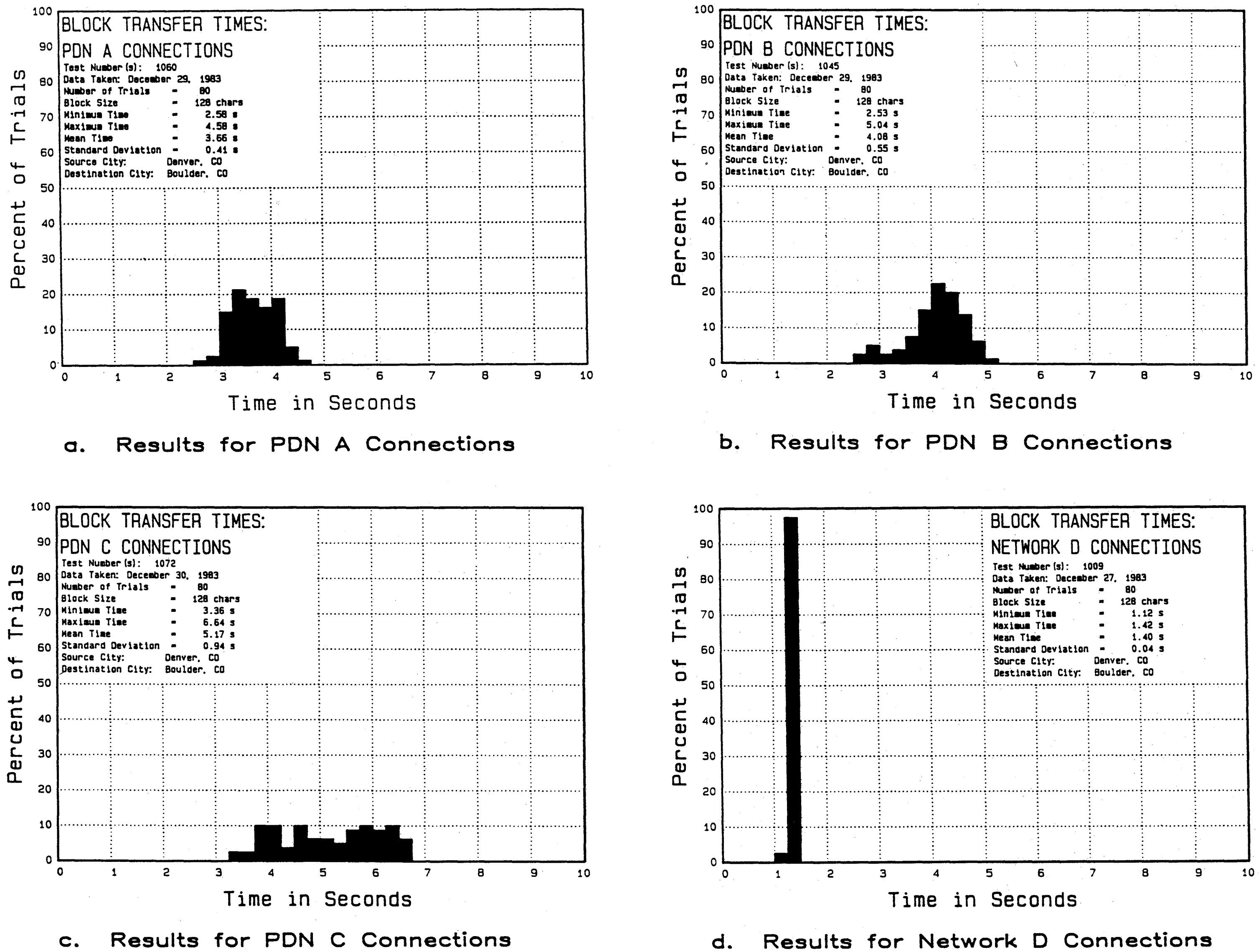
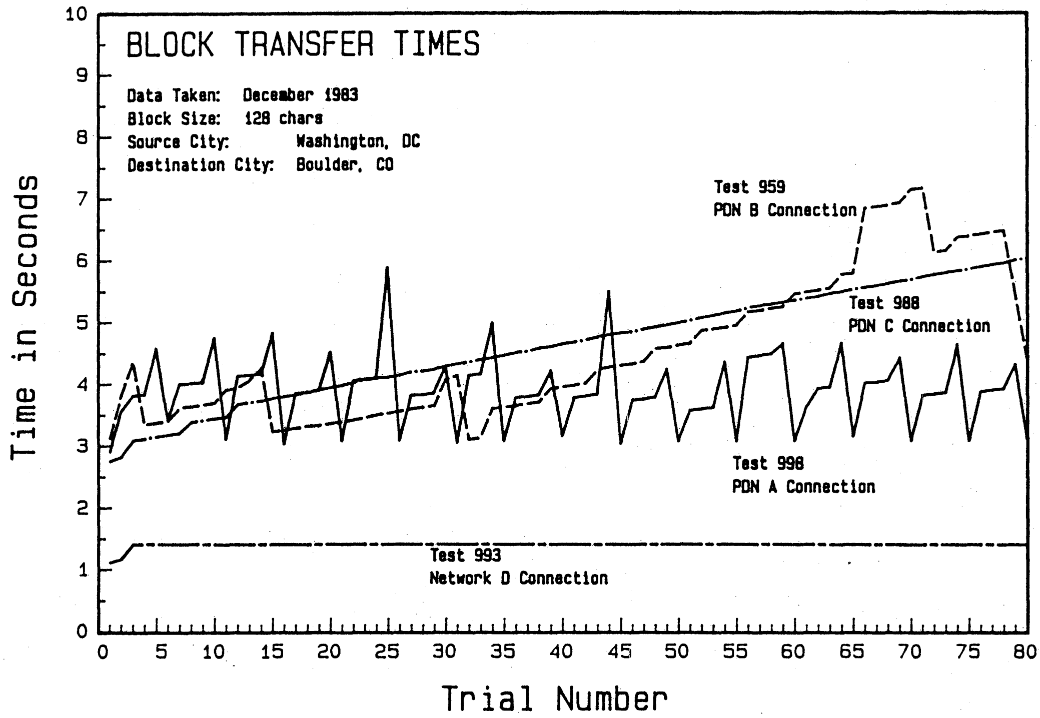
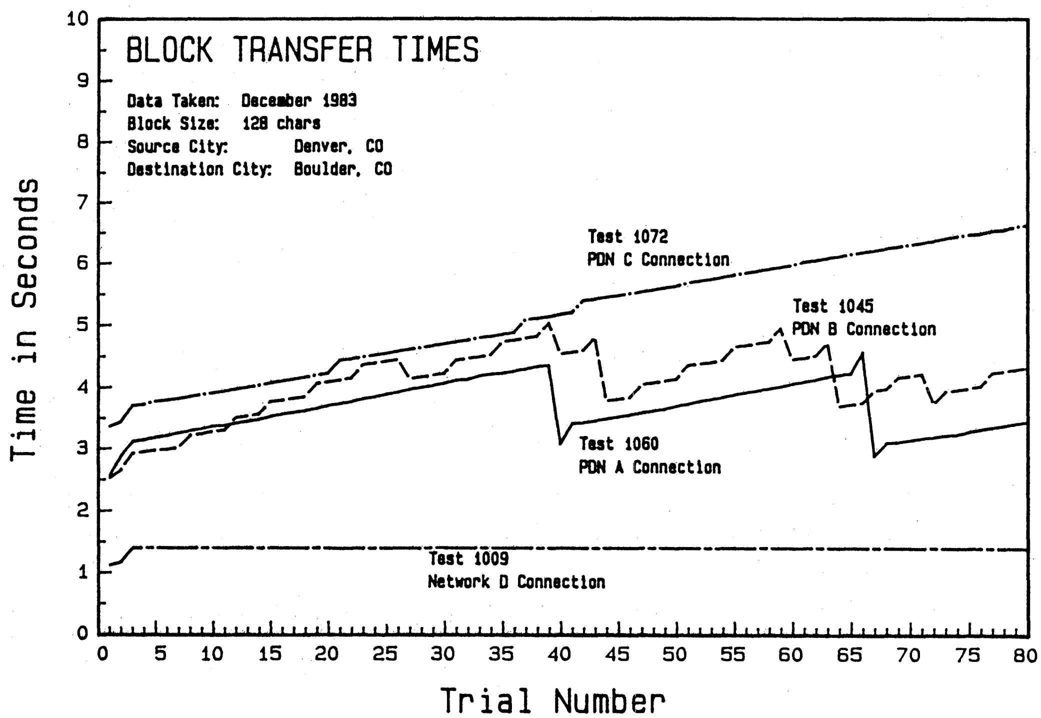


Figure 41. Block transfer time histograms for Denver, CO.



a. Washington, DC Results



b. Denver, CO Results

Figure 42. Block transfer time chronological plots.

delayed. An abnormally delayed WRITE COMPLETE response was interpreted as the result of an X-off signal issued by the network to the local operating system subsequent to the previous WRITE COMPLETE response. The X-off signal suspended transmission of user information to the network until a subsequent X-on signal was issued. Thus, each decrease in block transfer time shown by the plots in Figure 42 reflected the issuance of an X-off/X-on signal pair. The shorter block transfer times that ensued were the result of transfer through a less congested network.

Features of block transfer delay patterns that characterized connections over individual PDNs are discussed in the following paragraphs.

A. PDN A CONNECTIONS

For both the Washington and Denver tests, chronological plots of block transfer times for connections over PDN A formed a quasi-periodic sawtooth pattern. Each sharp increase in transfer time was followed by an even larger decrease for the next block, and each decrease was followed by another abnormal (but smaller) increase before the "normal" increase in block transfer time resumed (see, for example, blocks 24-28 in Test 998 in Figure 42a). As discussed above, these fluctuations were the result of X-off signals that interrupted the transmission of data from the source operating system to the network. The greater frequency and longer duration of X-off states on the Washington-Boulder link indicated that congestion was more common and more severe than on the Denver-Boulder link. This increased congestion no doubt contributed to the longer block transfer times observed in the Washington tests.

B. PDN B CONNECTIONS

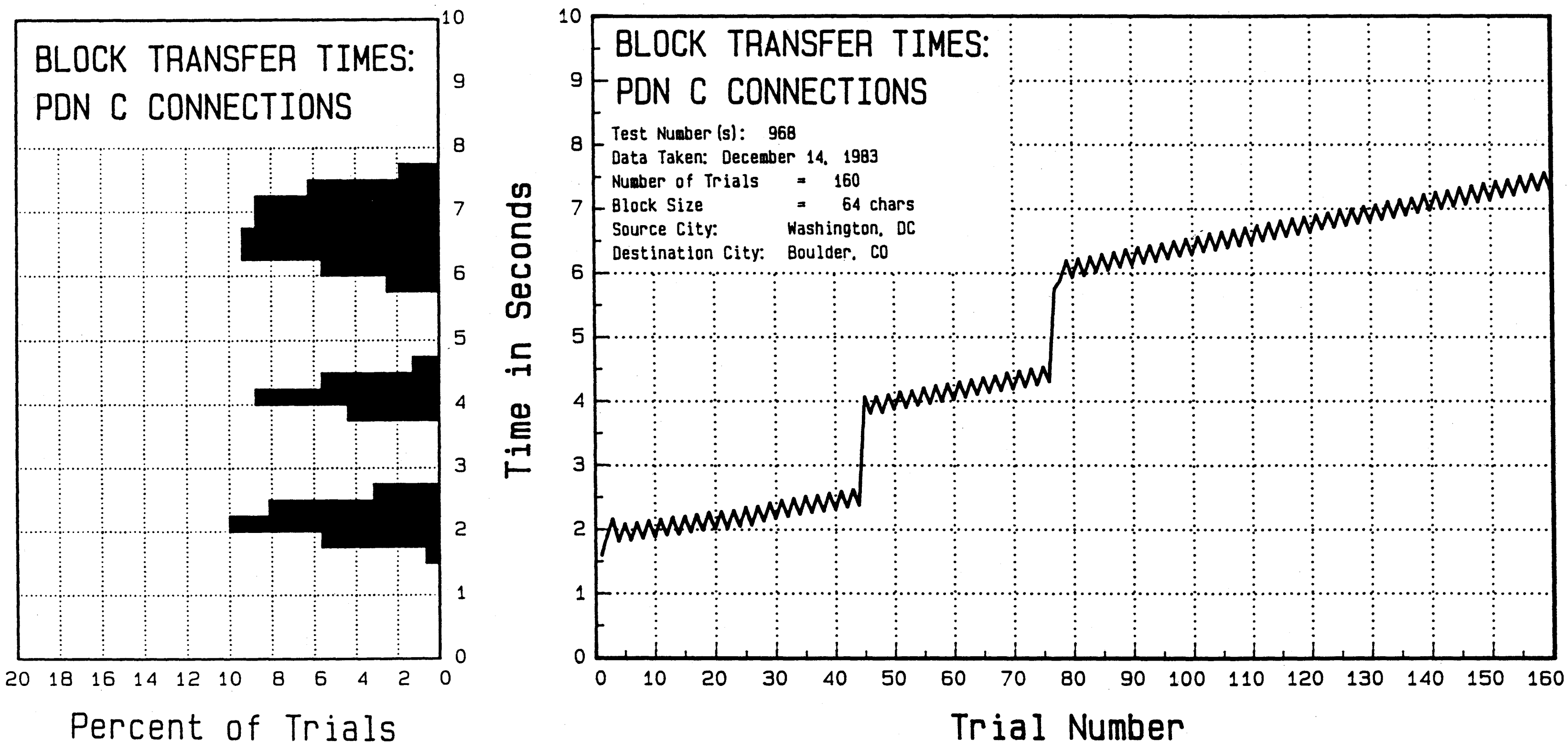
The chronological plots of block transfer times for connections over PDN B were rather irregular: they lacked both the quasi-periodicity of the patterns for connections over PDN A and the almost linearly increasing trend of the results for the connections over PDN C. Each plot revealed the occurrence of several X-off states at irregular intervals. They also included many brief intervals of "normally" increasing block transfer time separated by abrupt increases of about 1/5 second. As described previously, these abrupt increases in block transfer time were associated with abnormally long delays between the output of the affected block and the output of the preceding block. However, the cause of such delays is unknown.

C. PDN C CONNECTIONS

The chronological plots of block transfer time for connections over PDN C consisted of several intervals of "normally" increasing transfer time separated by abrupt increases of about 1/5 second. The latter were essentially the same size as those observed in connections over PDN B, and their cause is likewise unknown. No X-off was issued by PDN C during any test in which flow control was enabled. This indicated that PDN C was able to store a rather large amount of user data. As a result of the "steady" increase of block transfer time with trial number, and the absence of X-off signals, estimated values of Block Transfer Time for connections over PDN C under high utilization were strongly influenced by the amount of user information transferred in each test. For example, halving the amount of transmitted user data would have reduced mean values for the transfer of 128-character blocks by about 1/2 second.

Figure 43 illustrates the usefulness of chronological plots in the interpretation of delay distributions. Figure 43a shows a histogram of observed times for the transfer of 64-character blocks via a connection over PDN C in a typical high-utilization test. The most distinctive feature of this distribution is that it consists of three disjoint and rather similar modes. Figure 43b presents a chronological plot of block transfer times for the same test. This plot shows two large and abrupt increases of block transfer time that separated the observed values into three groups corresponding to the modes represented in the histogram. Each of these increases was associated with an abnormally long delay between the output of two successive blocks at the destination interface. They may indicate priority level slipping or a routing change through additional nodes.

Another distinctive feature of the chronological plot in Figure 43b is the small-amplitude sawtooth or ripple pattern. This pattern was observed in all high-utilization tests that transferred 64-character blocks, regardless of the network used (see, for example, the chronological plot of block transfer times for a connection over PDN B shown in Figure 49b). A detailed examination of the event histories revealed the same sawtooth pattern when intervals between the input of successive blocks were plotted as a function of block number. The pattern apparently was the joint result of block size, the size of a UNIX™



a. Histogram **b. Chronological Plot**

Figure 43. Relationship of histogram and chronological plot for a high utilization test.

buffer associated with the communication port of the (remote) test microcomputer, and the manner in which the operating system transferred characters from the DATA.X file into that buffer.

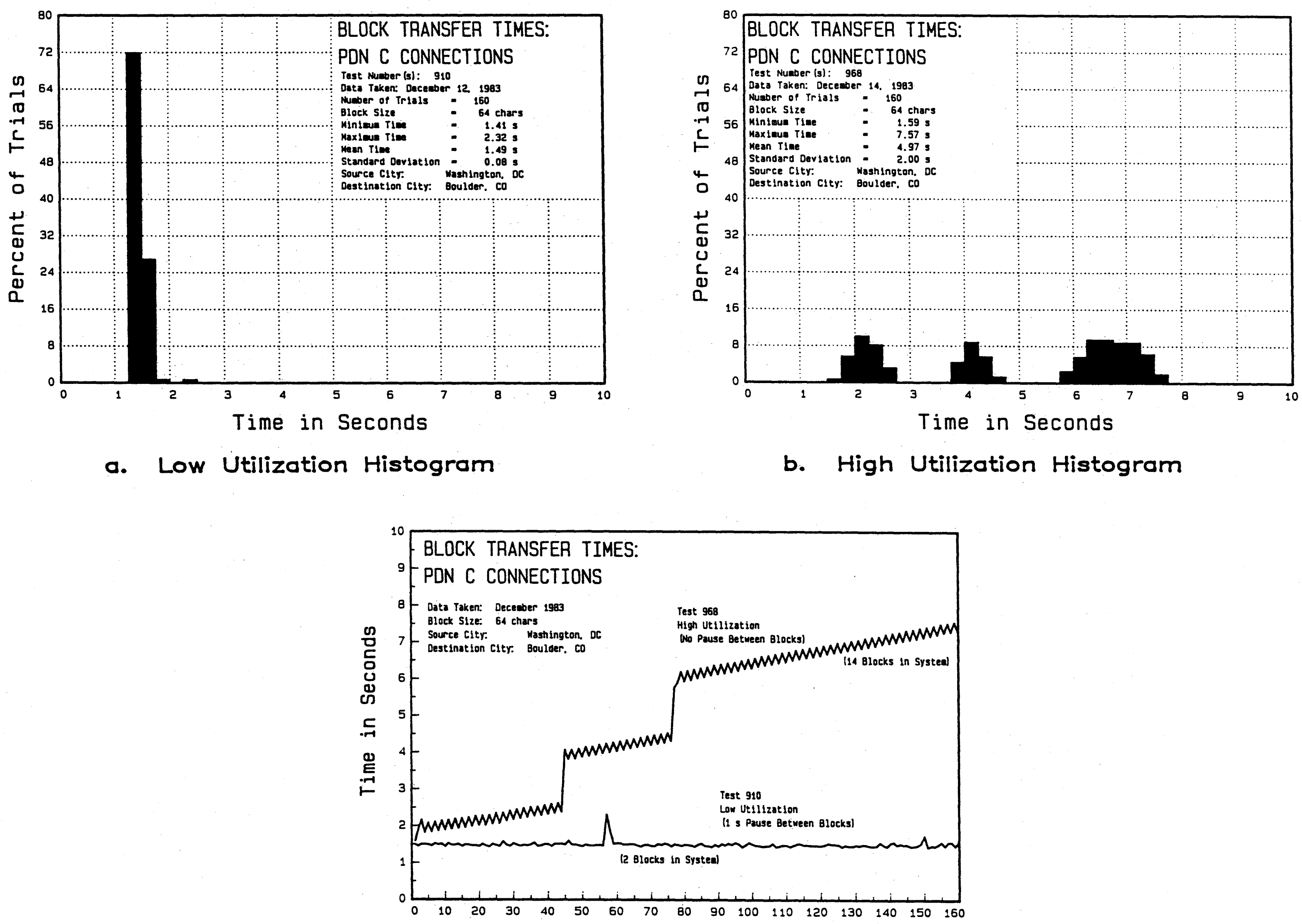
Histograms and chronological plots presented in Figure 44 illustrate the effect of utilization on block transfer times for the transfer of 64-character blocks via connections over PDN C. The high-utilization case is illustrated by the same test used in Figure 43. Between the large upward jumps in block transfer time, the chronological plot exhibits an increasing trend in delay values similar to that shown in Figure 42 for 128-character blocks. Both the histogram and the chronological plot for low utilization show that the delays are characterized by low variance. The ripple pattern is absent for low-utilization transfer because the additional delay between the input of successive blocks permitted each block to clear the UNIX™ communication port buffer before input of the next block. The prominent delay time spike for block 57 may have been caused by an error resulting in retransmission of the block.

The histograms in Figure 45 illustrate the effect of satellite transmission on block transfer times. As expected, an extra 250-millisecond delay is associated with transfer on the satellite link. Except for a few somewhat larger values, observed block transfer times were nearly constant for both the satellite and terrestrial links. The occasional longer delays may have resulted from routine system management activities performed by one of the test computers.

Selected components of the total block transfer time for transfer via a connection over a typical public data network are described in Figure 46. Example calculations are also provided.

The box plots and fitted regression lines in Figure 47 depict the effect on block transfer time of a major network upgrade by Uninet. The dominant effect of the improvement was the reduction of mean block transfer delay by approximately 1.75 seconds for all block sizes. The upgrade also significantly reduced the variation in the middle 50% of the delay values. The "old" Uninet results are based on five user information transfer tests not listed in Table 14.

Chronological plots in Figure 48 contrast a typical user information transfer test (914) on a connection over PDN C with an abnormal test (911) conducted only about 20 minutes earlier. Test 911 began with block transfer

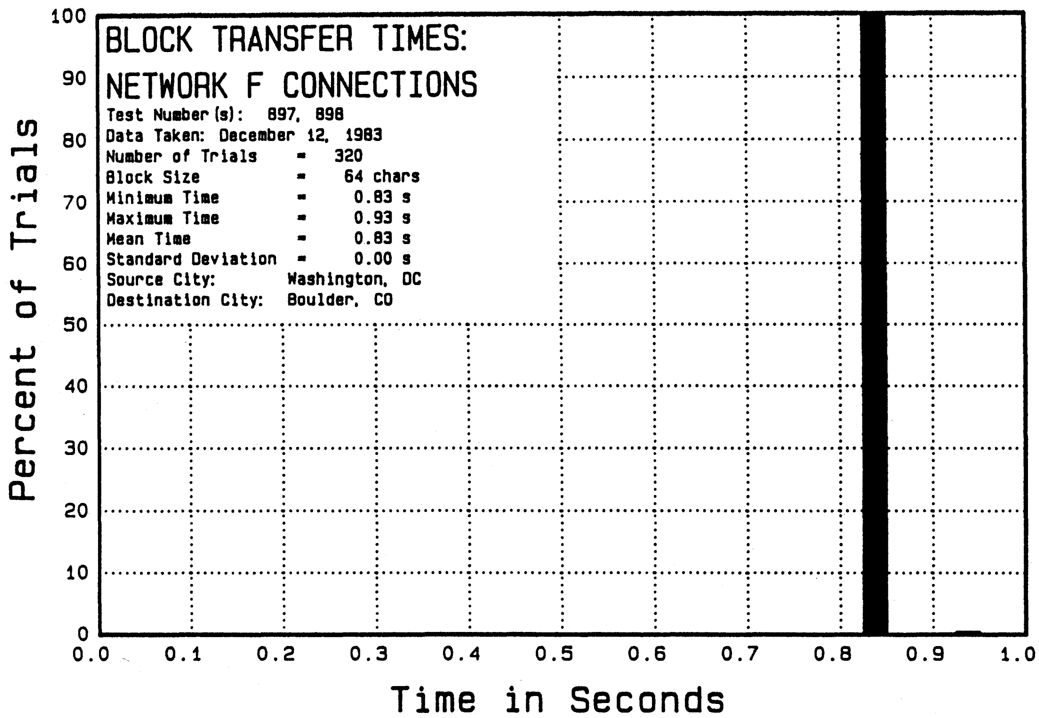


a. Low Utilization Histogram

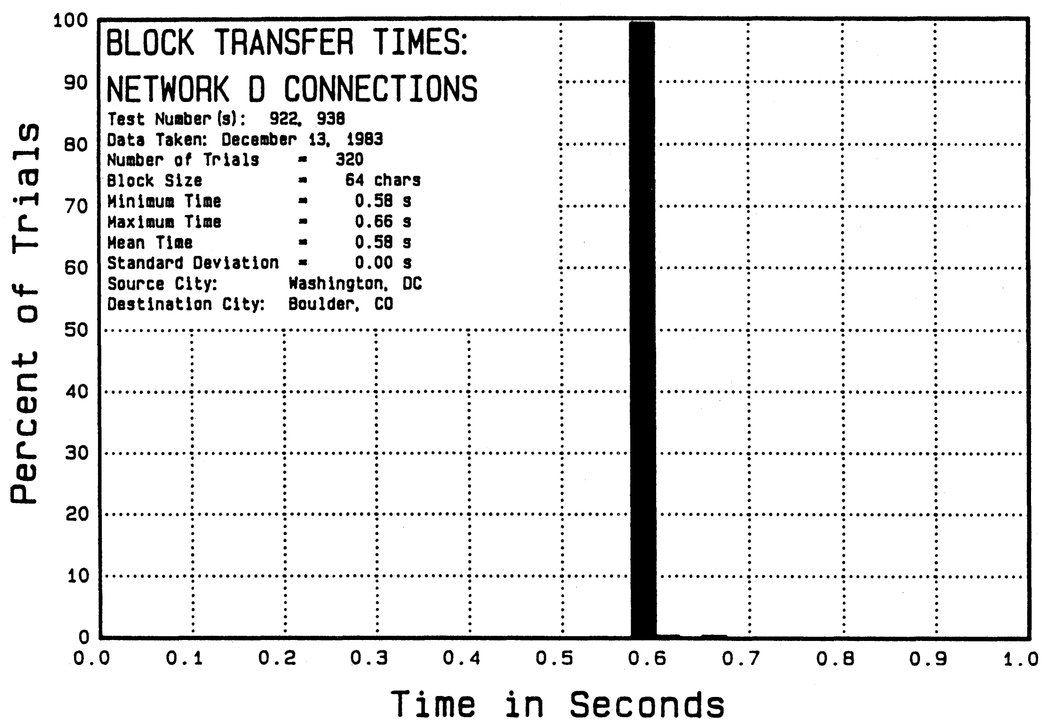
b. High Utilization Histogram

c. Chronological Plots

Figure 44. Effect of utilization on block transfer times for PDN C connections.

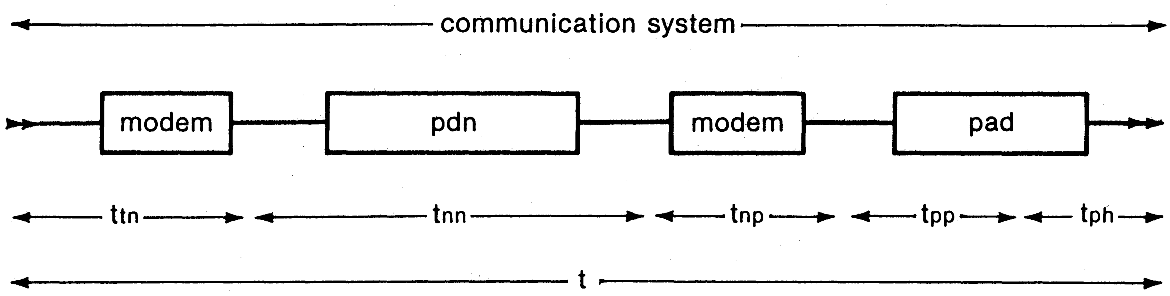


a. Satellite Transmission (Network F)



b. Terrestrial Transmission (Network D)

Figure 45. Effect of satellite transmission on block transfer times.



$$t = t_{tn} + t_{nn} + t_{np} + t_{pp} + t_{ph}$$

where

t = user information transfer time

t_{tn} = terminal to network transfer time

$$= \frac{(64 \text{ char} + 1 \text{ char}) \times 10 \text{ bits/char}}{1200 \text{ bits/sec}} = 541.67 \text{ ms}$$

t_{nn} = network transfer time

t_{np} = network to pad transfer time

$$= \frac{(3 \text{ char} + 3 \text{ char} + 65 \text{ char}) \times 8 \text{ bits/char}}{9600 \text{ bits/sec}} = 56.67 \text{ ms}$$

t_{pp} = pad transfer time

≈ 10 ms

t_{ph} = pad to host transfer time

$= 541.67$ ms

Then,

$$\begin{aligned} t_{nn} &= t - (t_{tn} + t_{np} + t_{pp} + t_{ph}) \\ &\approx t - (541.67 \text{ ms} + 56.67 \text{ ms} + 10 \text{ ms} + 541.67 \text{ ms}) \\ &\approx t - 1150.01 \text{ ms} \\ &\approx t - 1.1500 \text{ sec.} \end{aligned}$$

Figure 46. Components of block transfer time for transfer via a PDN.

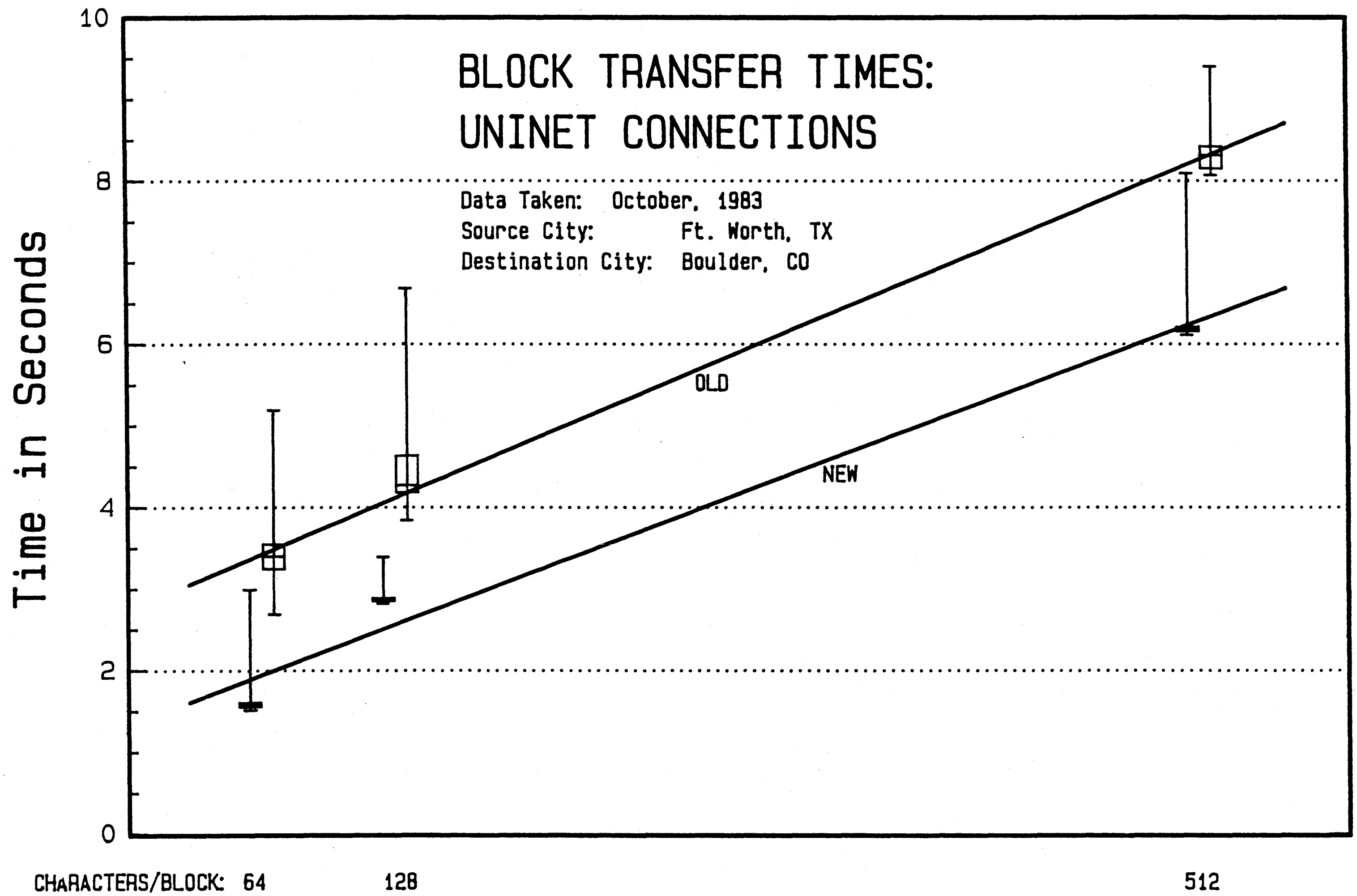


Figure 47. Effect of a major network upgrade on block transfer time.

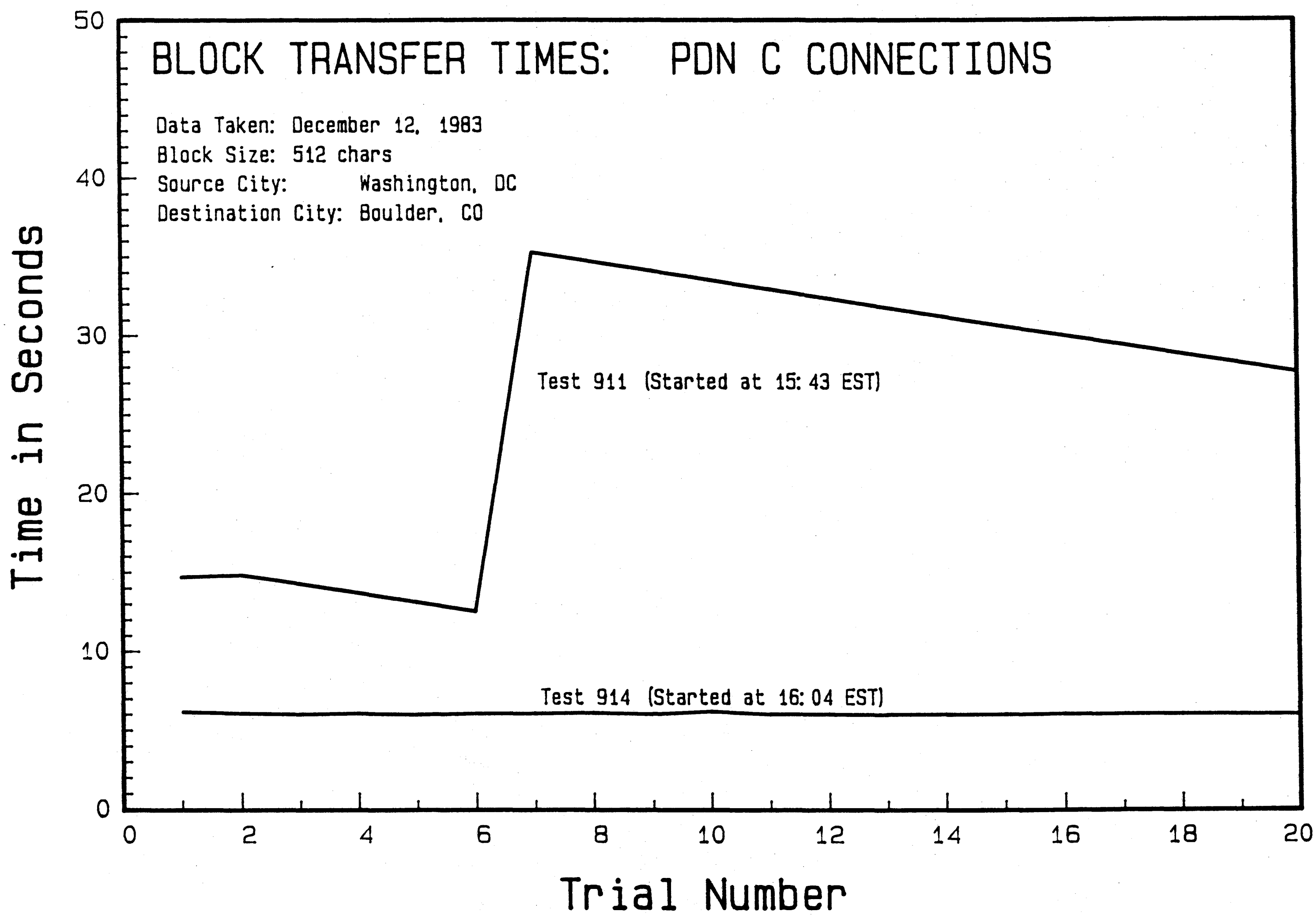


Figure 48. Block transfer times for an abnormal test.

delays nearly double the normal value. After the transfer of six blocks, there was an abrupt 29-second increase in block transfer time followed by a steady decline in delay values. Test 911 was the only test exhibiting such behavior.

5.3.2 User Fraction of Block Transfer Time

User Fraction of Block Transfer Time is the ratio of the average block transfer time for which the user is responsible to the average total performance time for block transfer attempts that result in Successful Block Transfer.

Only the destination interface is relevant in performance time allocation for block transfer. In the ITS tests, measured user delays associated with the block transfer function were produced when RECV read the satellite clock (following delivery of a block) to obtain times for the READ COMPLETE (End of Block Transfer) event and the subsequent READ command. Total user delay for a given block transfer attempt was determined by the number of previously transmitted blocks that were delivered during the associated performance period. Hence, measured values were generally integral multiples of 133 milliseconds, the time required for RECV to read the satellite clock. In some cases, a block transfer attempt began while RECV was reading the satellite clock, so the user performance time included only part of interval required to read the clock.

In low-utilization tests on connections over a PDN, only the most recent of previously transmitted blocks was delivered during a typical block transfer performance period.[4] The resulting average user performance times for block transfer were largely independent of both the block size and the PDN connection. On the other hand, total performance time was strongly influenced by block size, as described in Section 5.3.1 and shown in Figure 39. The corresponding measured values of User Fraction of Block Transfer Time reflected this block size effect. Typical results are summarized in Table 16, and values for individual tests are presented in Appendix G.

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[4]A unique exception to this behavior occurred in Test 911 on a connection over PDN C. As noted in Section 5.3.1 and illustrated in Figure 48, block transfer times in this test were abnormally long. An examination of user delays recorded in the associated performance outcome file showed that as many as six or seven previously transmitted blocks were delivered during some block transfer performance periods.

Table 16. User Delay Summary for Block Transfer via PDNs at Low Utilization

Block Size (characters)	Block Transfer Time (seconds)	User Fraction of Block Transfer Time
64	1.6-1.8	0.08-0.09
120	2.7-3.1	0.04-0.05
518	6.0-7.0	0.016-0.021

In low-utilization tests on connections over the switched telephone networks (D and F), a given block was generally delivered to the destination user before the next block was transmitted by the source user, so the associated user delay was zero. Exceptions occurred when the first block was delivered during transfer of the second block. Hence, measured values of User Fraction of Block Transfer Time for such tests were either zero or near zero.

In high-utilization tests, observed block transfer times were longer than those for comparable low-utilization conditions because data spent more time in system queues prior to delivery. Block transfer times for successive trials formed characteristic patterns that depended on block size and the network connection. Some typical patterns for medium blocks are illustrated in Figure 42, and a pattern for short blocks is shown in Figure 43. For short or medium blocks transferred via a PDN, one or more previously transmitted blocks were generally delivered during a block transfer attempt, and observed user delays for individual trials varied accordingly. Otherwise, only the most recent of previously transmitted blocks was usually delivered during a performance period. Values of User Fraction of Block Transfer Time measured in high-utilization tests are summarized in Table 17. Parameter estimates and associated information for individual tests are presented in Appendix G.

All of the observed user delay during block transfer was the result of interface monitor procedures performed by RECV and would not have occurred otherwise. Hence, measured values of User Fraction of Block Transfer Time obtained in the ITS tests did not represent typical operating conditions. Moreover, these parameter values did not describe the influence of the measurement system on observed values of Block Transfer Time. As discussed in Section 5.3.7, the user/monitor procedures performed by RECV (i.e., reading the satellite clock following delivery of a block) did not impede user information output, and therefore had no effect on measured block transfer performance.

Table 17. User Delay Summary for Block Transfer at High Utilization

	PDN Connections		Network D Connections	
Block Size (characters)	Block Transfer Time (seconds)	User Fraction of Block Transfer Time	Block Transfer Time (seconds)	User Fraction of Block Transfer Time
64	2.4-5.0	0.18-0.22	0.78-0.79	0.17
128	3.6-6.8	0.07-0.11	1.40-1.41	0.093-0.094
512	6.7-8.7	0.016-0.023	4.47-4.48	0.028

5.3.3 Bit/Block Error Probabilities

Bit Error Probability is the (conditional) probability that the Incorrect Bit outcome occurs in a trial in which a bit is transferred from the source user to the intended destination user within the maximum performance period. The Incorrect Bit outcome occurs if the value of the transferred bit is incorrect. In a performance measurement, Bit Error Probability is estimated by the ratio of Incorrect Bit outcomes to the number of bit transfer attempts that result in Successful Bit Transfer or Incorrect Bit.

Block Error Probability is the (conditional) probability that the Incorrect Block outcome occurs in a trial in which a block is transferred from the source user to the intended destination user within the maximum performance period. The Incorrect Block outcome occurs if the content of the transferred block is incorrect (i.e., if one or more bits in the block are Incorrect Bits or when some, but not all, of the bits in the block are Lost Bits or Extra Bits). In a performance measurement, Incorrect Block Probability is estimated by the ratio of Incorrect Block outcomes to the number of block transfer attempts that result in Successful Block Transfer or Incorrect Block.

A. Bit Error Probabilities

Bit error results are summarized in Table 18. It shows numbers of bits transferred and incorrect bits, estimates of Bit Error Probability, and the corresponding upper and lower 95% confidence limits for several categories of network connections. Of a total of 17,506,608 bits transferred in 214 user information transfer tests, only 21 were received in error. These errors occurred as bursts in 3 tests: 11 errors in 3 consecutive characters in a test from Ft. Worth, 6 errors in 3 consecutive characters in a test from Seattle, and 4 errors in a single character in a test from Denver. Only the latter test involved a PDN (Network A). Measured bit error rates for transfer via connections over the PDNs and transfer via connections over Network D or F were $4/(13,903,664) = 2.9 \times 10^{-7}$ and $17/(3,602,944) = 4.7 \times 10^{-6}$, respectively. The measurements show the expected result that data transferred via the telephone network connections, which lacked error control, were more subject to bit errors than were data transferred via the PDN connections. The errors observed in the test via PDN A were almost certainly introduced in the terminal access link, which was a local telephone connection unprotected by error control. The differences in Bit Error Probability among the PDN connections are not statistically significant. The difference in Bit Error Probability between the combined data for connections over the PDNs and the data for connections over Networks D and F is significant at the 0.1% level.

B. Block Error Probabilities

Block error results are summarized in Table 19. Some significant points are highlighted below.

- Of 23,764 blocks transferred, 112 were received in error.
- All but 9 of the Incorrect Block outcomes occurred in transfer via connections over PDN A when flow control was not enabled, and all were due to bit loss. This phenomenon is explained more fully in Section 5.3.4. When flow control was enabled for PDN A, only 2 Incorrect Block outcomes occurred in 2000 blocks transferred.
- Flow control was not a significant factor for block errors in transfer via connections over PDN C, since an X-off was never issued by that network, even when flow control was enabled.
- Block errors in transfer via connections over Networks D and F, which inherently do not have flow control capability, did not

Table 18. Bit Error Summary

NETWORK CONNECTION	BITS TRANSFERRED ($B1_s + B1_e$)	INCORRECT BITS ($B1_e$)	BIT ERROR PROBABILITY		
			LOWER 95% CONFIDENCE LIMIT*	ESTIMATED MEAN	UPPER 95% CONFIDENCE LIMIT*
A	4 975 320 (61 tests)	4 (1 test)	6.9×10^{-8}	8.0×10^{-7}	3.5×10^{-6}
B	4 996 208 (61 tests)	0	0	0	1.2×10^{-6}
C	3 932 136 (48 tests)	0	0	0	1.5×10^{-6}
D	1 556 480 (19 tests)	0	0	0	3.8×10^{-6}
F	2 046 464 (25 tests)	17 (2 tests)	3.7×10^{-6}	8.3×10^{-6}	1.6×10^{-5}
All PDNs	13 903 664 (170 tests)	4 (1 test)	2.5×10^{-8}	2.9×10^{-7}	1.3×10^{-6}
D/F	3 602 944 (44 tests)	17 (2 tests)	2.1×10^{-6}	4.7×10^{-6}	9.1×10^{-6}
All Networks	17 506 608 (214 tests)	21 (3 tests)	5.7×10^{-7}	1.2×10^{-6}	2.2×10^{-6}

*When the number of failures is zero or one, the conditional probability of failure used to estimate confidence limits is 0.5.

Table 19. Block Error Summary

a. Flow Control Enabled

NETWORK CONNECTION	BLOCKS TRANSFERRED $(B2_s + B2_e)$	INCORRECT BLOCKS $(B2_e)$	BLOCK ERROR PROBABILITY		
			LOWER 95% CONFIDENCE LIMIT*	ESTIMATED MEAN	UPPER 95% CONFIDENCE LIMIT*
A	2 000 (23 tests)	2 (2 tests)	1.5×10^{-4}	1.0×10^{-3}	3.8×10^{-3}
B	5 159 (61 tests)	2 (1 test)	5.7×10^{-5}	3.9×10^{-4}	1.5×10^{-3}
C	3 140 (37 tests)	0	0	0	1.1×10^{-3}
All PDNs	10 299 (121 tests)	4 (3 tests)	1.2×10^{-4}	3.9×10^{-4}	1.0×10^{-3}

b. Flow Control Not Enabled

NETWORK CONNECTION	BLOCK SIZE (CHARACTERS)	BLOCKS TRANSFERRED $(B2_s + B2_e)$	INCORRECT BLOCKS $(B2_e)$	BLOCK ERROR PROBABILITY		
				LOWER 95% CONFIDENCE LIMIT*	ESTIMATED MEAN	UPPER 95% CONFIDENCE LIMIT*
A	64	1 914 (12 tests)	48 (1 test)	1.7×10^{-2}	2.5×10^{-2}	3.5×10^{-2}
	128	1 040 (13 tests)	12 (3 tests)	4.4×10^{-3}	1.2×10^{-2}	2.4×10^{-2}
	512	260 (13 tests)	43 (11 tests)	1.2×10^{-1}	1.7×10^{-1}	2.2×10^{-1}
C	64	480 (3 tests)	0	0	0	6.9×10^{-3}
	128	320 (4 tests)	1	0	3.1×10^{-3}	1.6×10^{-2}
	512	80 (4 tests)	0	0	0	3.9×10^{-2}
D	64	960 (6 tests)	0	0	0	3.4×10^{-3}
	128	560 (7 tests)	0	0	0	5.9×10^{-3}
	512	120 (6 tests)	0	0	0	2.7×10^{-2}
F	64	1 600 (10 tests)	1	0	6.2×10^{-4}	3.2×10^{-3}
	128	560 (7 tests)	3 (3 tests)	1.3×10^{-3}	5.4×10^{-3}	1.6×10^{-2}
	512	160 (8 tests)	0	0	0	2.0×10^{-2}

*When the number of failures is zero or one, the conditional probability of failure used to estimate confidence limits is 0.1.

differ significantly from those in transfer via connections over the PDNs with flow control enabled.

5.3.4 Bit/Block Loss Probabilities

Bit Loss Probability is the (conditional) probability that the Lost Bit outcome occurs in a trial in which a bit is transmitted by the source user and does not result in Refused Bit. The Lost Bit outcome occurs if the transmitted bit is not delivered to the intended destination user within the maximum performance period, and the system is responsible for the failure. In a performance measurement, Lost Bit Probability is estimated by the ratio of Lost Bit outcomes to the number of bit transfer attempts that result in Successful Bit Transfer, Incorrect Bit, or Lost Bit.

Block Loss Probability is the (conditional) probability that the Lost Block outcome occurs in a trial in which a block is transmitted by the source user and does not result in Refused Block. The Lost Block outcome occurs if no part of the transmitted block is delivered to the intended destination user within the maximum performance period, and the system is responsible for the failure. In a performance measurement, Lost Block Probability is estimated by the ratio of Lost Block outcomes to the number of block transfer attempts that result in Successful Block Transfer, Incorrect Block, or Lost Block.

A. Bit Loss Probabilities

Bit loss results are summarized in Table 20. As indicated in the previous section, most (i.e., 90%) of the observed bit loss occurred during tests on connections over PDN A without flow control. Such tests resulted in 21,792 lost bits out of 3,112,960 bits transmitted. This compared with only 8 lost bits out of 1,884,160 bits transmitted in flow-controlled tests. The corresponding estimated bit loss probabilities are 7.0×10^{-3} and 4.2×10^{-6}, respectively. The significance level of this difference is 10^{-7}%. The dramatically higher loss rate without flow control may be attributed to a relatively low data storage capacity for PDN A. This explanation is consistent with the frequent issuance of X-off signals when flow control was implemented on PDN A, as described in Section 5.3.1 (see Figure 42).

No bit loss was observed in the 1.6 million bits transmitted via connections over Network D. However, 1536 of the 2.0 million bits transmitted via connections over Network F were lost. This difference in performance is

Table 20. Bit Loss Summary

a. Flow Control Enabled

NETWORK CONNECTION	BITS TRANSMITTED ($B1_s + B1_e + B1_\ell$)	LOST BITS ($B1_\ell$)	BIT LOSS PROBABILITY		
			LOWER 95% CONFIDENCE LIMIT*	ESTIMATED MEAN	UPPER 95% CONFIDENCE LIMIT*
A	1 884 160 (23 tests)	8 (1 string; 1 test)	2.1×10^{-7}	4.2×10^{-6}	3.2×10^{-5}
B	4 997 120 (61 tests)	912 (1 string; 1 test)	9.5×10^{-6}	1.8×10^{-4}	1.4×10^{-3}
C	3 031 040 (37 tests)	0	0	0	5.1×10^{-4}
All PDNs	9 912 320 (121 tests)	920 (2 strings; 2 tests)	8.2×10^{-6}	9.3×10^{-5}	4.5×10^{-4}

b. Flow Control Not Enabled

NETWORK CONNECTION	BLOCK SIZE (CHARACTERS)	BITS TRANSMITTED ($B1_s + B1_e + B1_\ell$)	LOST BITS ($B1_\ell$)	BIT LOSS PROBABILITY		
				LOWER 95% CONFIDENCE LIMIT*	ESTIMATED MEAN	UPPER 95% CONFIDENCE LIMIT*
A	64	983 040 (12 tests)	7944 (37 strings; 1 test)	4.8×10^{-3}	8.1×10^{-3}	1.2×10^{-2}
	128	1 064 960 (13 tests)	1400 (8 strings; 3 tests)	2.8×10^{-4}	1.3×10^{-3}	3.0×10^{-3}
	512	1 064 960 (13 tests)	12448 (48 strings; 11 tests)	7.5×10^{-3}	1.2×10^{-2}	1.7×10^{-2}
C	64	245 760 (3 tests)	0	0	0	6.0×10^{-3}
	128	327 680 (4 tests)	24 (1 string; 1 test)	3.7×10^{-6}	7.3×10^{-5}	5.6×10^{-4}
	512	327 680 (4 tests)	0	0	0	4.5×10^{-3}
D	64	491 520 (6 tests)	0	0	0	3.0×10^{-3}
	128	573 440 (7 tests)	0	0	0	2.6×10^{-3}
	512	491 520 (6 tests)	0	0	0	3.0×10^{-3}
F	64	819 200 (10 tests)	264 (1 string; 1 test)	1.7×10^{-5}	3.2×10^{-4}	2.4×10^{-3}
	128	573 440 (7 tests)	1272 (2 strings; 2 tests)	2.0×10^{-4}	2.2×10^{-3}	1.1×10^{-2}
	512	655 360 (8 tests)	0	0	0	2.3×10^{-3}

*When the number of failures is zero or one, the conditional probability of failure used to estimate confidence limits is 0.998.

not statistically significant because the lost bits were clustered in only 3 strings.

Flow control was not a significant factor affecting bit loss in transfer via connections over PDN C since no X-off was issued when flow control was enabled. In fact, when flow control was enabled, there was no significant difference in bit loss among all the PDN connections.

B. Block Loss Probabilities

Block loss was infrequently observed; results obtained from an examination of the data are summarized below.

- o Loss occurred in only 2 tests; both transmitted short (64-character) blocks.

- o Six blocks were lost in a single test without flow control on a connection over PDN A from Washington, DC. Severe losses occurred in this test; specifically, 993 characters in 37 strings were lost. However, this was the only short block test on a connection over PDN A that experienced data loss.

- o One block was lost in a test on a connection over PDN B from Denver, CO. The block was included in a longer string of 114 lost characters. This test is described in more detail in the following section.

All lost blocks were included within longer strings of lost (undelivered) characters. Additionally,

- o character strings were usually lost independent of block boundaries, and

- o the length of lost strings varied from 1 to 204 characters.

Under normal operating conditions with flow control enabled, block loss during transfer via connections over any PDN was very rare; only 1 block was lost in 10,300 transmitted.

5.3.5 Extra Bit/Block Probabilities

Extra Bit Probability is the (conditional) probability that the Extra Bit outcome occurs in a trial in which a bit is received by the destination user and does not result in Refused Bit. The Extra Bit outcome occurs if the received bit was not output by the source user for delivery to the destination user. In a performance measurement, Extra Bit Probability is estimated by the ratio of Extra Bit outcomes to the number of bit transfer attempts that result in Successful Bit Transfer, Incorrect Bit, or Extra Bit.

Extra Block Probability is the (conditional) probability that the Extra Block outcome occurs in a trial in which a block is received by the destination user and does not result in Refused Block. The Extra Block outcome occurs if no part of the received block was output by the source user for delivery to the destination user (i.e., if the block transfer attempt includes only Extra Bit outcomes). In a performance measurement, Extra Block Probability is estimated by the ratio of Extra Block outcomes to the number of block transfer attempts that result in successful Block Transfer, Incorrect Block, or Extra Block.

A. Extra Bit Probabilities

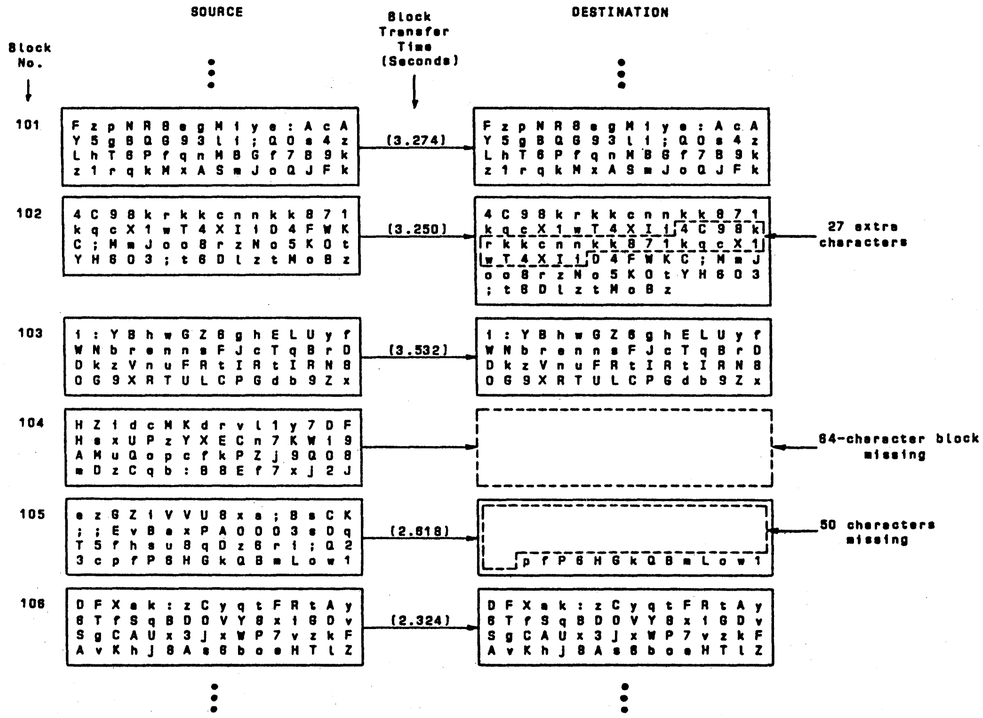
Only one episode of extra bits was observed in all 214 user information transfer tests; this occurred as a single string of extra characters during a test (1082) from Denver that transferred 64-character blocks on a connection over PDN B.

The test in question also included an episode of data loss that was closely associated with the extra data. Both anomalies are shown in Figure 49, which also demonstrates the capability and precision of the ITS-developed data reduction software. The specific data transfer failures observed are illustrated in Figure 49a and may be summarized as follows:

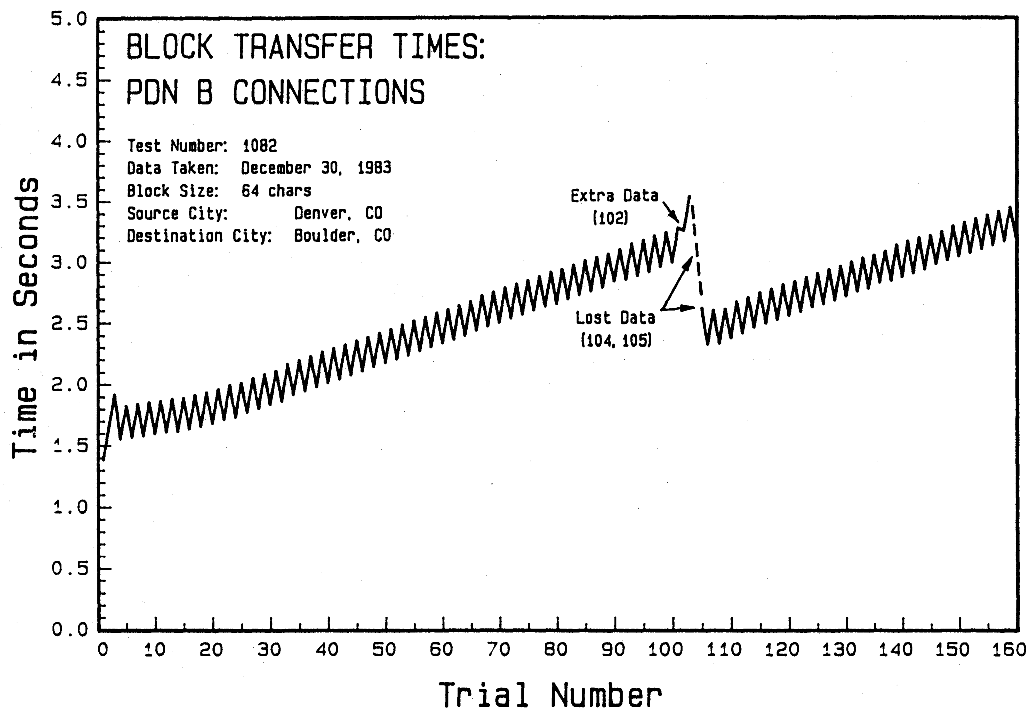
- o The first 27 characters of block 102 were duplicated in characters 28-54 of the received block; the block length was thereby increased to 91 characters. None of the received characters were altered in transmission.
- o Block 103 was received correctly.
- o The next 114 characters in succession were lost (not delivered). These comprised all of block 104 and the first 50 characters of block 105.

All other blocks transmitted during the test were received correctly.

Figure 49b is a chronological plot of the block transfer times observed in the anomalous test just described. A pronounced distortion in the transfer time curve is evident at precisely the point of the anomaly. The transfer time for block 102 was longer than expected because of the extra data included. The transfer time for block 103 was also longer than expected, probably because the additional delay in block 102 caused it to be stored longer in a network queue. No block transfer time is plotted for block 104 because this block was not



a. Transmitted and Received Data



b. Chronological Plot

Figure 49. Analysis of an observed block transfer anomaly.

delivered. The transfer time for block 105 was about 700 milliseconds shorter than expected, presumably for two reasons: first, it spent less time in network queues due to the absence of block 104; and second, the delivered block was 50 characters shorter than normal.

The chronological plot resumes its normal pattern with block 106. No irregularity in data input was associated with the observed anomaly, indicating that the anomaly did not occur on the terminal access link. It is almost certain that the anomaly occurred within the PDN, since the PDN-host access link was protected by retransmission error control under X.25 interface protocol.

B. Extra Block Probabilities

Of 18,353 blocks received, none was in the extra category. Hence, the measured value of Extra Block Probability was zero for connections over each network.

5.3.6 User Information Bit Transfer Rate

User Information Bit Transfer Rate for a transfer sample is the total number of Successful Bit Transfer outcomes in the sample divided by the input/output time (the larger of the input time and the output time) for the sample. The bit transfer rate is therefore the smaller of the rate at which user information bits are input to the system by the source user and the rate at which user information bits are output to the destination user by the system. User Information Bit Transfer Rate is a measure of throughput.

For the evaluation of long-term (steady-state) throughput in the ITS measurements, each test included only one trial--the largest single transfer sample that could be obtained from the test. This sample began with the interblock gap that followed the first block transfer attempt in the test. The start of sample input corresponded to Start of Block Transfer for the first block transfer attempt in the test, and the end of input corresponded to Start of Block Transfer for the last block transfer attempt in the test. The start of sample output corresponded to End of Block Transfer for the first block transfer attempt in the test, and end of output corresponded to End of Block Transfer for the last block transfer attempt in the test.

The two levels of utilization strongly influenced measured bit transfer rates. The effects are described in detail in the following paragraphs.

A. Low Utilization

Under low-utilization conditions, an additional delay of roughly 1 second was introduced (by means of the UNIX™ SLEEP command) between input of successive blocks. An outline of the input process is shown in Figure 50 for each block size. In the case of short (64-character) blocks, the entire block was stored immediately in the UNIX™ buffer associated with the network port, so the WRITE COMPLETE event occurred after a delay of only about 8 milliseconds, as shown in Figure 50a. The XMIT program then read the satellite clock, issued a 1-second SLEEP command, read the satellite clock a second time, and issued the WRITE for the next block. Meanwhile, the operating system transmitted the contents of the block to the network at the rate of 120 characters/second. As indicated in the figure, the interval between the input of successive blocks was nearly 1 second, and the total sample input time was about 159 seconds. The corresponding input processes and times for medium (128-character) and long (512-character) blocks are shown in Figures 50b and 50c, respectively. In both of these cases, however, the entire block could not be stored immediately in the network port buffer. As a consequence, the WRITE COMPLETE event did not occur until most of the block contents had been transmitted to the network by the operating system. Because each SLEEP interval extended only to the next whole second "tick" of the system clock, the input process was controlled by that clock. The intervals between the input of successive blocks (i.e., the interblock gaps at the source interface) were generally very close to an integer number of seconds, as shown in the figure.

Sample input times calculated on the basis of the model just described were 159, 158, and 95 seconds, respectively, for short, medium, and long blocks. Observed values generally differed from these by less than 1 second.

The output of user information blocks was not influenced by the system clock, and intervals between the delivery of successive blocks (i.e., the interblock gaps at the destination interface) were somewhat more variable than the input intervals. However, the total sample output time was generally close to the total input time; the output value was sometimes greater than and sometimes less than the input value.

Typical values of User Information Bit Transfer Rate ranged from 510 to 514 bps for short and medium blocks, whereas typical values for long blocks ranged from 810 to 825 bps. The corresponding sample input rates calculated

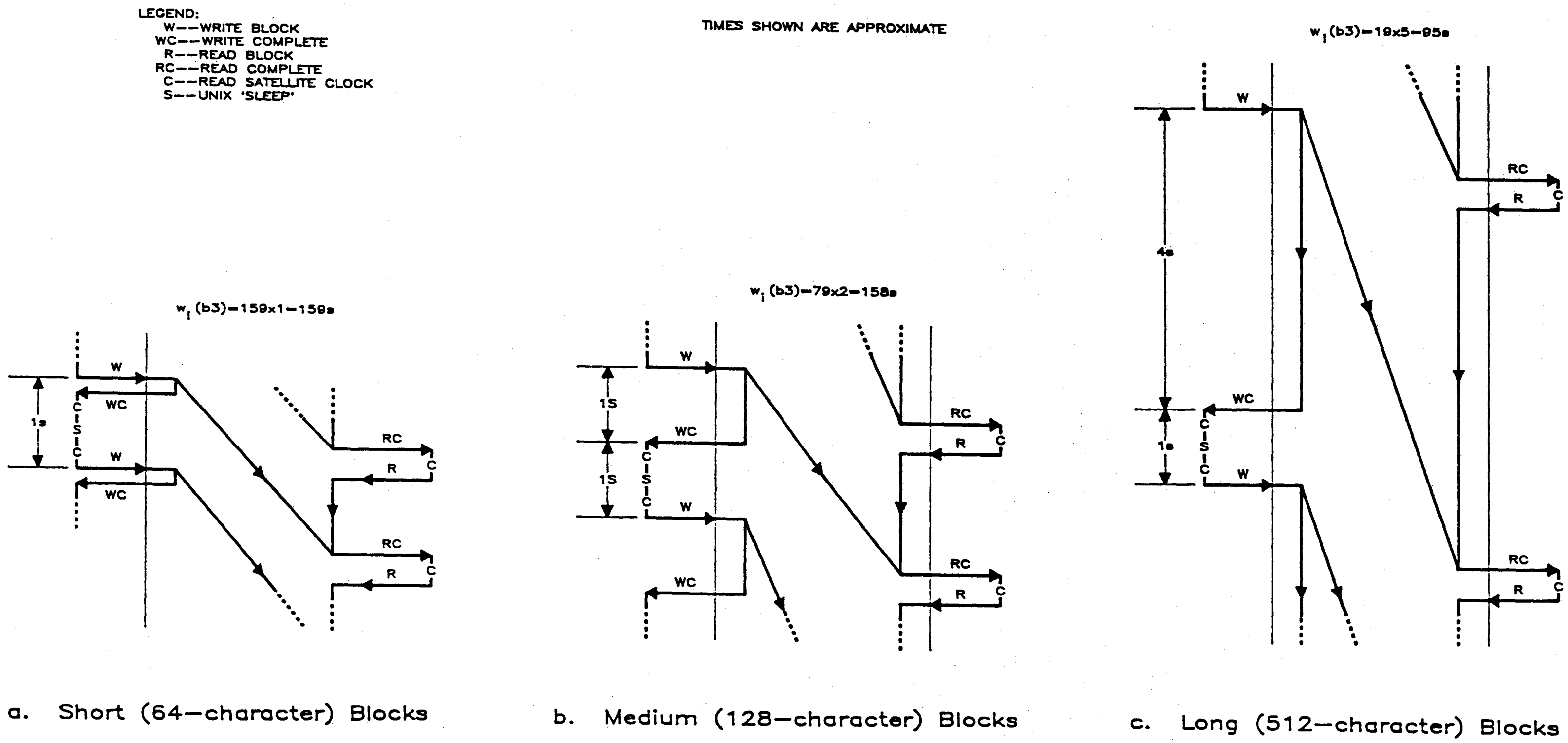


Figure 50. Summary of block input events for low utilization.

from the model described previously were 512, 512, and 819 bps for short, medium, and long blocks, respectively.

B. High Utilization

The "normal" input rate for connections over all networks was determined by the 1200 bps line speed from the terminal and corresponded to interblock gap durations of 0.542, 1.075, and 4.275 seconds for short, medium, and long blocks, respectively. The associated sample input rates were 945.2, 952.6, and 958.1 bps. Observed values for short blocks were modified by UNIX™ buffer effects as indicated in the discussion of Figure 43b in Section 5.3.1.

Significant departures from the "normal" input rate occurred as occasional longer delays between input of two successive blocks in tests on connections over PDN A and PDN B. These are thought to be the result of X-off events. No such delays were observed in tests conducted on connections over PDN C.

The "normal" output rate for connections over the PDNs was somewhat less than the "normal" input rate and was essentially independent of the PDN, as described in Section 5.3.1. The "normal" output rate was about 918, 925, and 930 bps for short, medium, and long blocks, respectively. On connections over Networks D and F, the "normal" output rate was nearly equal to the "normal" input rate because these networks lacked data storage capability.

Substantial departures from the "normal" output rate occurred on connections over PDNs A and B as occasional longer delays between output of two successive blocks. Some of these abnormal output delays were associated with X-off events at the source interface. The abnormal output delays resulted in lower overall throughput and increased variation in measured values of throughput.

Table 21 presents measured values of throughput for individual tests. These may be summarized as follows:

- PDN A Connections. Measured values of throughput for tests conducted from Washington, DC, were consistently lower and more dispersed than the values for tests from Denver, CO. These results were independent of block size and were associated with a higher incidence of X-off events in the Washington, DC, tests, as illustrated in Figure 42.

- PDN B Connections. The overall results were similar to those for connections over PDN A. However, for each block size, the largest throughput value from Washington was slightly larger than some of the values from Denver. The lowest throughput from Washington for each block size occurred in three successive

Table 21. Measured Values of User Information Bit Transfer Rate at High Utilization

BLOCK SIZE (CHARACTERS)	PDN A CONNECTIONS		PDN B CONNECTIONS		PDN C CONNECTIONS		NETWORK D CONNECTIONS	
	WASHINGTON DC	DENVER CO	WASHINGTON DC	DENVER CO	WASHINGTON DC	DENVER CO	WASHINGTON DC	DENVER CO
64	912.6* 868.7* 862.0* 862.0*	919.9* 919.5* 919.2* 916.5*	918.5 884.9* 838.2* 756.9*	919.7 918.0 917.9 915.8	922.6 886.7	920.0 920.0 918.8 907.5 849.2	944.9 944.9	944.9 944.9
128	775.5* 723.6* 668.9*	917.9* 910.8* 907.2* 885.5*	890.5* 876.2* 833.1* 782.5*	893.7* 892.3* 884.1*	919.8 903.4	920.1 920.0 917.0 899.6 862.5	952.2 952.2	952.3 952.2
512	920.3* 897.7* 869.7* 802.2*	929.9* 926.1* 925.9* 924.1*	929.2 925.8 917.3* 777.1*	930.0 930.0* 929.2 928.3* 927.9*	929.6 929.5 908.7	928.6 927.1 923.0 899.4	957.9 957.8	957.8 957.8

All values are expressed in bits/second
*x-off events observed in test

tests conducted around 3:00 AM. These tests included an abnormally large number of X-off events.

- PDN C Connections. These results were dissimilar to those for connections over PDNs A and B. Throughput values from Washington were in the same range as those from Denver, but the Denver values were more dispersed. No X-off events were observed.

- Network D Connections. For each block size, all measured values of throughput were within 0.5 bps of the theoretical values. The latter values were 945.2, 952.6, and 958.1 bps for short, medium, and long blocks, respectively. The tests on connections over Network D provided a convincing demonstration of measurement accuracy.

5.3.7 User Fraction of Input/Output Time

User Fraction of Input/Output Time for a transfer sample is the ratio of input/output time for which a user is responsible to the total input/output time. In a measurement of long-term (steady state) throughput, the input time should be approximately equal to the output time, and the associated User Fraction of Input/Output Time is the larger of the user fraction of input time and the user fraction of output time.

Samples for the evaluation of long-term throughput in the ITS measurements are described in the preceding section. For each such sample, the estimate of User Fraction of Input/Output Time was obtained by dividing the larger of the observed user performance times for input and output by the larger of the observed total performance times for input and output. Measured user delays associated with input and output were produced when the XMIT and RECV application programs read the satellite clock to obtain times for recorded interface events. The latter consisted of WRITE and WRITE COMPLETE events at the source user interface and READ and READ COMPLETE events at the destination user interface. In low-utilization tests, additional user delay during input resulted from the 1-second SLEEP command executed between the input of successive blocks.

XMIT read the satellite clock twice between the input of two successive blocks, whereas RECV read the clock only once between the output of two successive blocks. Consequently, user performance time for input was approximately twice that for output (the ratio was even greater in low-utilization tests). Thus, user input time was used to calculate the measured long-term value of User Fraction of Input/Output Time in each user information transfer test. For a given block size, the user performance time for input was largely determined by measurement system characteristics. It was independent of the network connection. However, this user time was strongly affected by block size, owing to the different numbers of block transfer attempts included in a throughput sample. In low-utilization tests, user performance times for input were in the ranges 157.1-158.1 seconds, 97.9-99.6 seconds, and 21.0-22.1 seconds for short (64-character), medium (128-character), and long (512-character) blocks, respectively. In high-utilization tests, observed user performance times for input were even more closely clustered: the ranges for short, medium, and long blocks were 42.67-42.77 seconds, 21.22-21.27 seconds, and 5.11-5.12 seconds, respectively.

As described in the preceding section, total performance times for input and output in low-utilization tests were nearly equal, had a relatively small variance, and were largely determined (for a given block size) by characteristics of the input process. The resulting estimates of User Fraction of Input/Output Time were approximately 0.99, 0.63, and 0.23 for short, medium, and long blocks, respectively.

In high-utilization tests on connections over the PDNs, total performance times were generally a few seconds longer for output than for input, especially for connections over PDN C. As described previously, performance time for output in tests on connections over a PDN consisted of two contrasting components:

- o a "normal" delay associated with a nearly uniform output rate independent of the network connection (but somewhat dependent on block size) and
- o an additional random delay associated with the occasional occurrence of abnormally long intervals between the delivery of two successive blocks.

For a given block size, the variability of the latter delays was largely responsible for variations in measured values of User Fraction of Input/Output Time. These values were in the ranges 0.46-0.49, 0.18-0.24, and 0.051-0.061 for short, medium, and long blocks, respectively. For tests on connections over network D, where input and output times were nearly constant, measured values of User Fraction of Input/Output Time for short, medium, and long blocks were 0.50, 0.25, and 0.063, respectively.

All observed user delay in input and output was the result of interface monitor functions performed by the XMIT and RECV programs; they would not have occurred otherwise. Hence, values of User Fraction of Input/Output Time obtained in the ITS measurements did not represent typical operating conditions. Furthermore, as described below, these parameter values did not accurately describe the influence of the measurement system on observed values of User Information Bit Transfer Rate and cannot be used to calculate user-independent estimates of throughput.

As discussed previously, the operating system of the source computer included a buffer that contained characters that had been input to the system and were awaiting transmission to the network. As long as this buffer was not emptied while XMIT performed user/monitor procedures (e.g., reading the satellite clock) between the input of successive blocks, these procedures did not impede data input. Similarly, the operating system of the host (destination) computer included a buffer that contained characters that had been received from the network and were waiting to be read by the user. As long as this buffer was not filled while RECV conducted its user/monitor procedures between the delivery of successive blocks, these procedures did not impede data output.

In high-utilization tests on connections over PDN D, the observed input/output rate was essentially equal to that determined by the access line speed of 1200 bps. This demonstrated that user/monitor procedures did not affect the input/output rate under high utilization conditions. In low-utilization tests, an examination of the input history showed that the inclusion of the 1-second SLEEP following the input of a block allowed the network port buffer to be emptied before input of the subsequent block. Under these conditions, the user/monitor procedures carried out by XMIT did impede data input, but their effect on the input rate was less than indicated by the measured value of the user fraction of sample input time. The output rate under low-utilization conditions was nearly the same as the input rate and was not affected by user/monitor procedures performed by RECV.

5.3.8 Transfer Denial Probability

Transfer Denial Probability is the (conditional) probability that the Transfer Denial outcome occurs for a transfer sample that does not result in a Rejected Sample (i.e., in user nonperformance). The Transfer Denial outcome occurs for a transfer sample if

- o the measured value of any of the four "supported" performance parameters for the sample (Bit Error Probability, Bit Loss Probability, Extra Bit Probability, and User Information Bit Transfer Rate) is worse than the associated threshold of acceptability and

- o the system is responsible for the failure.

In a performance measurement, Transfer Denial Probability is estimated by the ratio of Transfer Denial outcomes to the number of transfer samples that result in Successful Transfer or Transfer Denial.

The threshold of acceptability for a failure probability is defined by ANS X3.102 to be the fourth root of the associated specified value, and the threshold of acceptability for User Information Bit Transfer Rate is one-third of the specified value. In the ITS measurements, specified parameter values used in Transfer Denial estimation were 10^{-8} for each of the three failure probabilities and 1000 bps for User Information Transfer Rate. The corresponding threshold values were 10^{-2} for the failure probabilities and 333 bps for the bit transfer rate.

ANS X3.102 indirectly specifies the size of a transfer sample by stipulating that it must be sufficiently large to estimate each supported failure probability parameter (at its threshold value) with a relative precision of at least 50% at the 95% confidence level. According to Miles (1984), at least 18 bit transfer failures (of a given type) must be observed to achieve the precision specified (assuming independent trials). This requires a sample size of at least $18/10^{-2}$=1800 bits. Since transfer samples should consist of an integer number of successive block transfer attempts, the selected samples included 4 short blocks (2048 bits), 2 medium blocks (2048 bits), or 1 long block (4096 bits). A given transfer sample included the interblock gap preceding each block contained in the sample.

Of 6866 transfer samples selected in 214 user information transfer tests, 81 resulted in Transfer Denial. The latter included

- o 75 Transfer Denial outcomes due to bit loss in 14 tests on connections over PDN A without flow control,

- o one Transfer Denial outcome in a test on a connection over PDN B (with flow control) in which the numbers of both Extra Bit and Lost Bit outcomes were excessively high,

- o one Transfer Denial outcome due to bit loss in a test on a connection over PDN C (without flow control),

- one Transfer Denial outcome due to unacceptably low throughput in test number 911 (sample number 6) on a connection over PDN C (see Figure 48), and

- three Transfer Denial outcomes due to bit loss in tests on connections over network F.

Most (93%) instances of Transfer Denial were observed in tests on connections over PDN A without flow control. Transfer on connections over PDN A was characterized by frequent bit loss without flow control and frequent X-off events with flow control. Both observations are probable manifestations of relatively small network buffers.

If tests on connections over PDN A without flow control are excluded from the measurement, 5644 transfer samples remain. Only 16 of these resulted in Transfer Denial, which corresponds to an estimated Transfer Denial Probability of $6/5644 = 1 \times 10^{-3}$.

5.4 Measurement Problems and Solutions

Specific tools and techniques for the measurement of data communication performance in accordance with ANS X3.102 and ANS X3.141 were developed and implemented during the current ITS program. One of the more valuable results of this program was the experience acquired in dealing with the problems encountered in conducting the measurements. This section describes a few of the more significant problems and outlines ways in which they were (or may be) overcome.

5.4.1 Latin Square vs Randomized Blocks

A major element of the ITS experiment design was the arrangement of tests from each source city in the form of a 4x4 Latin square, where rows were days of the week and columns were times of day. Tests on connections over each of 4 networks occurred exactly once in each row and in each column. The purpose was to test connections over each network unbiasedly so as to determine whether days of the week or times of day contributed systematic variation.

Experience showed that such a design was too highly structured to be desirable. Relatively few of the Latin squares were completed for various reasons--the specified network could not be accessed at the specified time, or the measuring or recording equipment did not function correctly. While some incomplete Latin squares can be analyzed, the results may not be satisfactory because they are more difficult to interpret. In the ITS measurements, enough nalyzed (Appendix H) to indicate that time of day (during normal was not a substantial systematic source of variation.

f the potential difficulties in conducting tests at a prescribed commended that a Latin square design not be used to determine the effects of time factors, and that the simpler and readily analyzed randomized block design be used. In other words, the network connection to be tested at any particular time of day is selected at random, subject to the usual condition that connections over all networks be tested equally often. For example, if connections over 4 networks A, B, C, and D are to be tested and 16 time periods are available, each network letter can be written on 4 slips of paper and the slips thoroughly mixed and drawn blindly. (Tables of random permutations, with numbers not repeated, are also available (Moses and Oakford, 1963).) If one or more tests cannot be performed at the prescribed times, they can then be performed at the end with negligible effect on the design, though there could be a logistics problem if this process extends the tests from a particular city into another week. It is not even necessary that all network connections be tested equally often, but it is desirable, in order to achieve the desired precision of parameter estimation.

The only loss as the result of abandoning the Latin square is the ability to test whether day of week and time of day separately contribute systematic variations (e.g., to Access Time). One can still test whether they jointly contribute using a modified F test as outlined in Appendix H.

5.4.2 Efficient Testing

If an experiment has the purpose of characterizing an entire multiuser network (rather than demonstrating measurement methods and obtaining some representative performance values as in the ITS program), then the experiment design should be optimized by seeking the shortest possible confidence intervals for the performance parameters of most interest on the given budget. Variations among trials within tests, among tests within user pairs, and among user pairs all may contribute to the length of the confidence interval. The variation among user pairs will be relatively imprecisely determined because there are fewer user pairs than tests or trials; hence, it is desirable to increase their number as much as the budget permits (see Appendix H.2.4). The cost of adding a user pair is large compared to the cost of adding another test for a user pair already selected or adding another trial to a test already scheduled, but the gain in precision may be much greater. The optimal number of trials within a test is proportional to the standard deviation among the trials; likewise the optimal number of tests for each user pair is proportional to the standard deviation among tests, and the optimal number of user pairs is proportional to the standard deviation among user pairs. The optimal numbers also depend on the unit costs, so no precise design calculations can be made without knowing costs and standard deviations, but design can be guided qualitatively by these considerations.

5.4.3 Clock Synchronization

After the testing was completed and the data processing undertaken, it was discovered that a few tests contained time discrepancies implying that one of the clock receivers was out of synchronization with the NBS time standard. The clock at the host site was not visible to the operator, so a flashing LED indicating a synchronization failure could go unnoticed.

Because the clock displays a special symbol after the numerical time digits, a software check was available. If the clock was in synchronization with the transponded time, the symbol was a blank space (ASCII 32). Otherwise, some other printable character (such as ".", "*", "#", or "?" denoting a 1, 5, 50, or 500 millisecond error, respectively) was displayed. Although this symbol was displayed on the screen when setting the system clock to the NBS time, it was not available to the software in the short format used to read the clock during the ITS testing.

Resetting the clock at the host site before every test would have enabled the operator to observe the sync (or quality indicator) character on the CRT at the remote terminal site. However, even this procedure would not have detected the loss of synchronization in the middle of a test. On the basis of experience in the ITS measurements, the satellite clock should have been read using a format with an additional digit for the quality indicator, which was then checked for a specified tolerance. A test could then have been aborted or a message written to both the operator and a file if the observed tolerance was excessive.

Another factor that must be considered in carrying out international measurements is that the GOES satellites were intended for use in the Western Hemisphere and are not visible from Central Europe or the Far East. One possible solution to the clock synchronization problem for tests conducted from the latter regions would be to use one of the computers as a master and the other as a slave. The slave would be set from the master before each test and an offset taken into account. This would be possible if the communication path between the two sites were a bilateral analog (circuit-switched) connection such as a commercial dial-up line. It would not work on a digital store-and-forward network because of the delays. The offset would have to be calculated from half of the "round-robin" transit time minus, of course, any internal computer delays.

5.4.4 Switching among Networks

The host computer used for the ITS testing program was a multiuser system with five asynchronous ports. Three ports were assigned to engineers and programmers working on software development, and another was assigned to a dial-in line. This allocation provided only one port for testing connections over all three PDNs. It was therefore necessary to construct a switch that connected each PDN (via a 9600 bps modem and an X.25 PAD) to a single 1200 bps asynchronous computer port. Because PDN C required a PAD whose settings differed from those for the other networks, it was not possible to use a simple switch that connected all PDNs to a single PAD. Furthermore, the availability of only two PADs eliminated another simple configuration containing a separate PAD for each PDN.

The arrangement devised for the ITS tests used two RS-232 switch boxes, and is shown in Figure 51. The illustrated scheme was the least costly solution to the switching problem, but it required an operator to perform the switching at the host site. The need for an operator at the host site was sometimes a significant inconvenience, especially in early morning tests conducted from the Eastern or Central time zones. For example, when a test was scheduled to start at 8:30 a.m. (EST) in Washington, DC, it was only 6:30 a.m. (MST) in Boulder. The most satisfactory (and most expensive) approach is to eliminate the need for switching by providing a separate PAD and port for each network. Another approach is to construct a switch that can be controlled from the remote terminal site.

6. SUMMARY AND CONCLUSIONS

As stated in Section 3, the performance measurement program had two overall objectives. The first objective was to develop a comprehensive

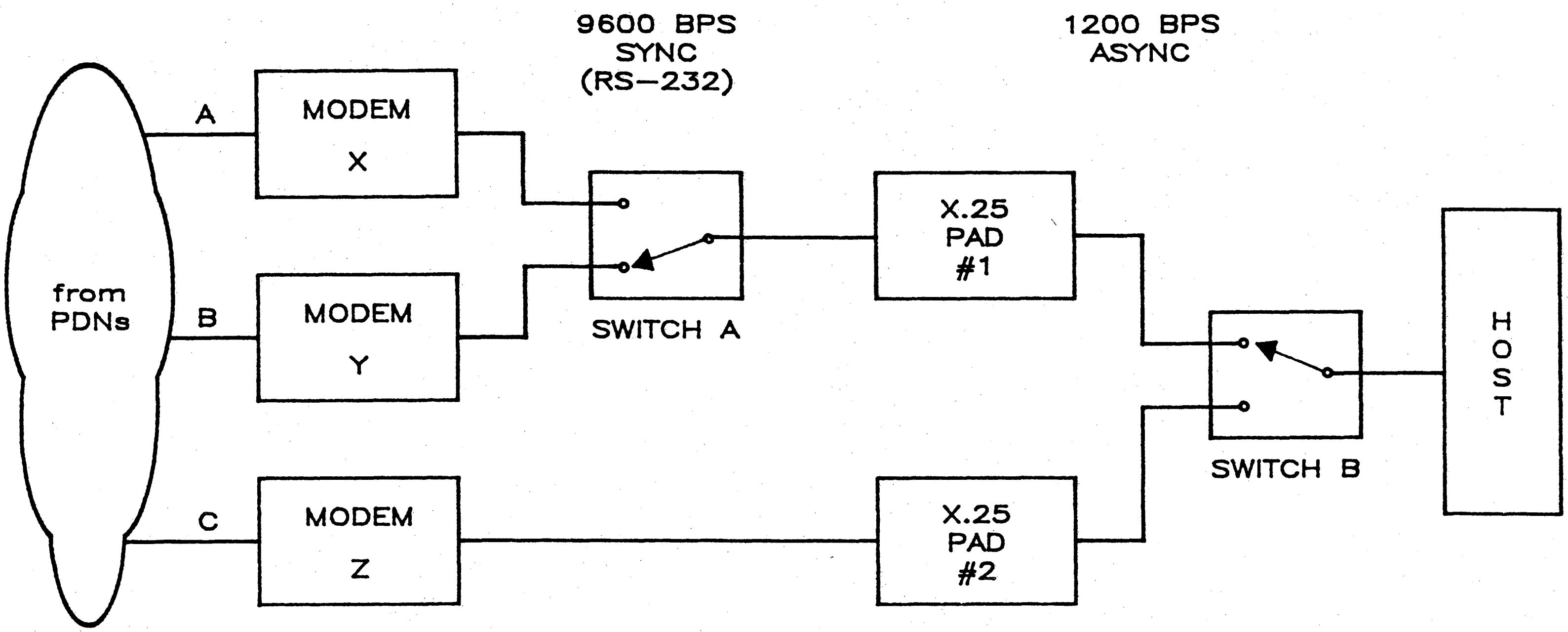


Figure 51. Switch selection of a single PDN for the host computer.

measurement system to assess data communication systems and services in accordance with American National Standards X3.102 and X3.141. The second objective was to demonstrate the applicability of this system by obtaining some typical values to characterize the end-to-end performance of data communication services provided by connections over three competing public data networks, the public switched telephone network, and the Federal Telecommunications System. It was anticipated that the measurement technology and performance data developed in this program would facilitate future data communication performance studies and, as a consequence, improve the matching of offered systems and services with user needs. This section briefly summarizes the major results of the performance measurement program in the context of these objectives, then concludes with some general observations.

6.1 Measurement Technology Development

The ITS measurement program produced a substantial improvement in previously existing measurement technology in each of the four phases of the measurement process defined in ANS X3.141. Key elements of the experiment design, data extraction, data reduction, and data analysis functions were implemented in computer programs that are now available for general use. In addition, a number of display programs were developed to facilitate test data analysis and a set of special purpose programs was developed to enable extracted data files to be automatically reduced and analyzed by using a single operator command. These software tools should greatly facilitate subsequent measurements.[5]

The ITS measurement program stimulated the development of a systematic procedure for designing data communication performance measurement experiments, and provided the first comprehensive implementation of it. The design procedure addresses each of the three major classes of performance measurement experiments: performance characterization, hypothesis test, and analysis of factor effects. The experiment conducted by ITS included elements of each of these generic experiment types. The measurement software development in the course of this work included a computer program that automates the important step of selecting measurement sample sizes. The use of the program can substantially reduce the time and cost of measurement experiments.

[5]They are in fact currently being used in packet-switched service performance measurements by several organizations.

Data extraction computer programs developed during the earlier ARPANET measurements were substantially enhanced in the course of the ITS experiment. The call originator (XMIT) program was redesigned so that it can readily access a wide variety of different data communication systems. All that is required to adapt this program to a different access protocol is to specify the relevant sequence of access commands and responses in an ASCII text file. The data extraction programs are written in C language to execute under the UNIX™ operating system and can be installed and run on many different computers, including commercially available computers that might be used in implementing portable test equipment. They could also be adapted to run under other operating systems with similar system calls. This flexibility should make the data extraction programs widely useful in future measurement applications.

A graphical tool that proved to be extremely useful in designing the data extraction programs, and one that has wide applicability to other efforts, is the session profile. The session profile is a comprehensive and concise presentation of the sequence of activities and events that comprise an individual test. Each interface event displayed in the profile represents either an input signal that the data extraction program must provide to the system, or an output signal that the system may provide in response. The chronological event sequence for a monitored pair of interfaces thus defines precisely which functions the data extraction program must accomplish during a test. Possible exception (failure) conditions are also clearly represented.

The data reduction procedures used in the ARPANET measurements were revised to address the important real-world situation in which there is dependence between events occurring at the two monitored interfaces. These revisions brought the data reduction procedures into full conformance with the final version of ANS X3.141 and will ensure an accurate evaluation of the user influence on performance in a wide range of measurement situations. The data reduction procedures were also modified to include the recording of pairs of successive failures. This enhancement facilitates the consideration of dependence between trials in the calculation of confidence limits associated with parameter estimates. A final major revision in the data reduction system was the addition of procedures to select and evaluate transfer samples for the measurement of availability and throughput parameters.

The most substantial measurement technology enhancement implemented in processing the collected data was the development of an automated performance data analysis system. This system, which is implemented in a machine-independent FORTRAN computer program, calculates performance parameter estimates and their confidence limits for individual tests and for pooled data from selected sets of tests. The program estimates the autocorrelation among successive trials in a test to account for their possible dependence. Such dependence can have a substantial effect on the precision achieved in a measurement. The program estimates the variance between tests to evaluate factor effects and to determine how data from different tests may be pooled, either to improve the precision of a parameter estimate or to provide an overall characterization of a multiuser network.

A very useful set of auxiliary data display programs was also developed to facilitate reduction and analysis of delay data. These programs enable test operators to rapidly generate tables and report-quality graphs, including box plots, histograms, chronological plots, and regression plots, to summarize results of individual tests or collections of tests. These graphs are extremely valuable in identifying factor effects and performance trends. The data display programs enable an operator to evaluate key test results while an experiment is still in progress. This can improve measurement efficiency and enhance the value of the results ultimately produced.

Key elements of the data extraction, data reduction, and data analysis programs described above were connected by a set of linkage programs to automate the processing of extracted performance data. Using the linkage programs, the program operator's issuance of a single command ("DO") causes the system to (1) prepare extracted performance data for input to the reduction process, (2) execute the three reduction programs, (3) prepare reduced performance data for input to the analysis process, (4) execute the analysis program, and (5) format the analysis program's output for presentation in a measurement results summary. These linkage programs greatly facilitate the processing of test data by eliminating the need for operator involvement in the editing and transfer of data files between the extraction, reduction, and analysis programs.

6.2 Measurement Results

The ITS measurement program also produced a substantial volume of data characterizing the performance of the selected end-to-end data communication services. The most significant measurement results are summarized by parameter below.

The ITS measurements revealed a substantial difference in Access Time between connections established via the three public data networks on the one hand, and those established via the public switched telephone network, on the other. The average Access Time for connections established via a PDN was about 43 seconds; the corresponding value for the PSTN connections was about 36 seconds. The observed difference can be attributed largely to PDN login and virtual circuit establishment time. Interestingly, the average Access Time for FTS connections was almost as long as that of the PDN connections--about 42 seconds. The lowest variance of Access Time was observed in the PSTN connections; the highest was observed in the PDN connections.

One factor that obviously influenced the Access Time observed in connections over a PDN was the type of signaling--tone or pulse--employed on the switched access line. In one typical comparison, the mean Access Time for PDN connections accessed by tone signaling was 9 seconds lower than that for connections accessed by pulse signaling. The number of PDN connections established by pulse signaling can be expected to decline as newer switching equipment is installed in the exchange networks.

An analysis of Access Time components indicated that a large proportion of the access delay experienced by public data network users is a result of factors outside the PDN boundaries, and thus outside the control of the PDN service provider. Even if host computer login time were excluded, the access delay outside the PDN would still be more than four times greater than that within it. An obvious implication is that efforts to reduce the PDN connection time (e.g., transit delay for X.25 Call Request and Call Accepted packets) will do little to improve the customer's perception of service quality when switched access lines are employed. The Access Time experience by PDN users can, of course, be reduced substantially through the use of leased access arrangements. The virtual circuit connection times quoted by PDN service providers are commonly in the range of 2 to 3 seconds.

As expected, the measurements revealed a substantial difference in the likelihood of the various access failures. Incorrect Access was never observed and Access Outage was limited to a few anomalous incidents, but Access Denial (system blocking) was extremely common (12% of all trials). There were significant differences in Access Denial Probability among connection types.

The lowest Access Denial Probability was observed in connections over the PSTN (no Access Denials were observed). The Access Denial Probabilities for connections over PDNs A and B and the Federal Telecommunications System were about the same (0.05-0.07). The corresponding value for connections over PDN C was substantially higher.

The observed values for Disengagement Time were influenced by two major factors: the entity being disengaged (source or destination user) and the type of connection being disengaged (connections over a PDN or connections over a switched telephone network). The Disengagement Times measured for the source (call originating) user were substantially longer than those measured for the destination (nonoriginating) user in connections over both the PDNs and the telephone networks. This was a result of the additional steps required in the former disengagement process (e.g., logging out of the host computer after RECV program termination). The Disengagement Times observed for PDN connections were significantly longer and more variable than those observed for telephone connections. These differences were attributed to longer transit delays for the disengagement request and response signals in the PDN connections, and, in the case of source disengagement, to the process of detaching from the PDN itself.

No Disengagement Denial outcomes were observed for connections over the telephone networks. For connections over the PDNs, the destination user Disengagement Denial Probability was negligible but the source user Disengagement Denial Probability was rather high (0.07-0.08). The latter denials were always associated with a failure to disconnect the switched access line.

The Block Transfer Times measured for connections over the PDNs were substantially longer, and generally more variable, than those measured for connections over the PSTN. This is largely attributable to the storage of user data in the PDN switches. Under high utilization, the mean Block Transfer Time for 128-character blocks transferred via PDN connections ranged between 3.8 and 5.9 seconds; the corresponding value for PSTN connections was 1.4 seconds. A block size effect on Block Transfer Time was clearly shown for both the PSTN and PDN connections: the relationship was precisely linear for the PSTN connections and roughly linear for the PDN connections.

The Block Transfer Time measurements for connections over the PDNs showed strong dependence between successive trials under continuous input.

Chronological plots of these measurements revealed a characteristic dependence pattern for each network connection. Data obtained using PDN A exhibited a quasi-periodic pattern in which the delay increased linearly from a base value for several successive blocks, then abruptly decreased to a value roughly equal to the original base value. The increase in delay is attributable to the queuing of user data in the network; the abrupt decrease is attributable to the issuance of an X-off signal, which interrupts data input and enables the network queues to empty. Data obtained using PDN B connections also showed increases in delay followed by abrupt decreases, but the pattern was much less strongly periodic than that observed for PDN A connections. The data for PDN C connections showed a remarkable pattern in which successive block transfer times increased almost linearly throughout a test, and never returned to the base value. These results indicate that PDN C had a substantial capability to buffer packets in transit between users. In one test, no fewer than 896 bits of user data were stored in the network at the end of the input phase. It appears that PDN C never issued an X-off signal in any connection established during the ITS testing.

In all tests on connections over a PDN, the mean and variance of Block Transfer Time were strongly influenced by "utilization"--the continuity or intermittency of user data input to the system. The observed Block Transfer Times were longer and more variable under high utilization (continuous input) than under low utilization (input of each block separated by a 1-second delay). As an example, the average 128-character Block Transfer Time observed in high-utilization tests on connections over PDN B was 4.4 seconds, with a variance of 2.2 seconds; the corresponding low utilization values were 2.8 seconds and 0.01 seconds, respectively.

The aggregate Bit Error Probability for all user information transfer tests was 1.2×10^{-6}. As expected, the Bit Error Probability was significantly lower for connections over a PDN (2.9×10^{-7}) than for connections over the telephone networks (4.7×10^{-6}). This difference is attributable to the use of retransmission error control within the PDNs. The few bit errors that were observed in tests utilizing PDN connections were almost certainly introduced in the terminal access lines, which were not protected by error control.

The Block Error and Transfer Denial outcomes observed in the user information transfer tests were largely derivative of a more fundamental transmission failure--bit loss. Such outcomes were common in tests on connections over PDN A in which flow control was not enabled. They occurred as a result of a packet network's limited capacity to store (buffer) user information. Bit loss was not limited to the high-utilization tests, but was clearly linked to the absence of flow control: only two incidents of bit loss were observed in tests on connections over a PDN when flow control was enabled. These incidents resulted in an overall Bit Loss Probability of 9.3×10^{-5}. The differences in Bit Loss Probability among the PDN connections under flow controlled conditions were not statistically significant. The loss of an entire block was observed in only two tests.

Only one incident of extra bit delivery was observed during the tests. The extra bits were an exact duplicate of 27 characters transmitted immediately preceding the duplication. The duplication event was followed by the loss of a long string of characters. It is probable that this anomaly occurred within the PDN.

The most significant User Information Bit Transfer Rate values were those measured under high utilization, since the values measured under low utilization were strongly influenced by user delays between the input of successive blocks. The values measured under high utilization in connections over network D (PSTN) were within 0.5 bps of the theoretically predicted values; this provided a strong validation of the measurement system accuracy. In high-utilization tests on connections over the PDNs, the User Bit Transfer Rate values ranged between 669 bps and 929 bps.[6]

Surprisingly, the choice of PDN, source city, and block length did not significantly influence User Information Bit Transfer Rate in the PDN connections tested. By far the most significant influence on User Bit Transfer Rate was the frequency and duration of X-off events. This is understandable, since such events suspend the input of user data.

6.3 Conclusions

The performance measurement technology developed in this program is believed to represent the most comprehensive implementation of American National Standards X3.102 and X3.141 to date. It may, in fact, be the most

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[6]The latter value represents a throughput efficiency of 77% if the start and stop bits appended to each user information byte for asynchronous transmission are counted as system overhead. Because of the start and stop bits, the maximum possible throughput of 8-bit bytes transmitted asynchronously on a 1200 bps line is 960 bps.

comprehensive data communication performance assessment capability currently available. Although the measurement results presented in this report are limited in geographical coverage and time, they appear to be the most comprehensive user-oriented assessment of data communication performance published to date. They will provide a useful baseline for the development and assessment of future data communication systems and services. It will be necessary to develop and implement similar user-oriented measures of digital voice and video communication performance in order to optimize the provision of services in future Integrated Services Digital Networks. Technical studies directed toward that goal have been initiated at the Institute for Telecommunication Sciences.

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APPENDIX A: SUMMARY OF AMERICAN NATIONAL STANDARD X3.102

This appendix presents a summary of American National Standard X3.102, "Data Communication Systems and Services--User-Oriented Performance Parameters" (ANSI, 1983). This standard defines 21 parameters that provide uniform means to quantitatively describe the performance of data communication systems and services from the viewpoint of the end user. The parameters apply to any digital communication system or service, and are independent of transmission medium, network topology, and protocol.

Figure A-1 summarizes the process used to develop the ANS X3.102 performance parameters. It consists of four steps:

1. Model Development. Certain universal performance characteristics of existing and proposed data communication services were identified. These characteristics were then consolidated in a user-oriented model of the data communication process which provided a system-independent basis for the performance parameter definitions.

2. Function Definition. Three primary functions that are performed during a typical data communication session (access, user information transfer, and disengagement) were identified. These functions were defined in terms of beginning and ending events that can be observed at a user/system interface.

3. Outcome Definition. Each primary function was examined to determine possible outcomes that might result from an individual performance trial. These outcomes were grouped into three categories: successful performance, incorrect performance, and nonperformance. These categories correspond respectively to the three performance criteria that most frequently concern end users: speed, accuracy, and reliability.

4. Parameter Selection. Each primary function was considered with respect to each performance criterion, and one or more parameters were selected to represent each function/criterion pair. These primary parameters, which describe the joint performance of the users and the system, consist of performance times, rates, and failure probabilities. A set of ancillary parameters was formulated to describe the effect of user delay on the primary speed parameters.

The subsections that follow describe each of these steps in greater detail.

A.1 Model Development

The first step in developing the ANS X3.102 performance parameters was to construct a functional, user-oriented model of the data communication process

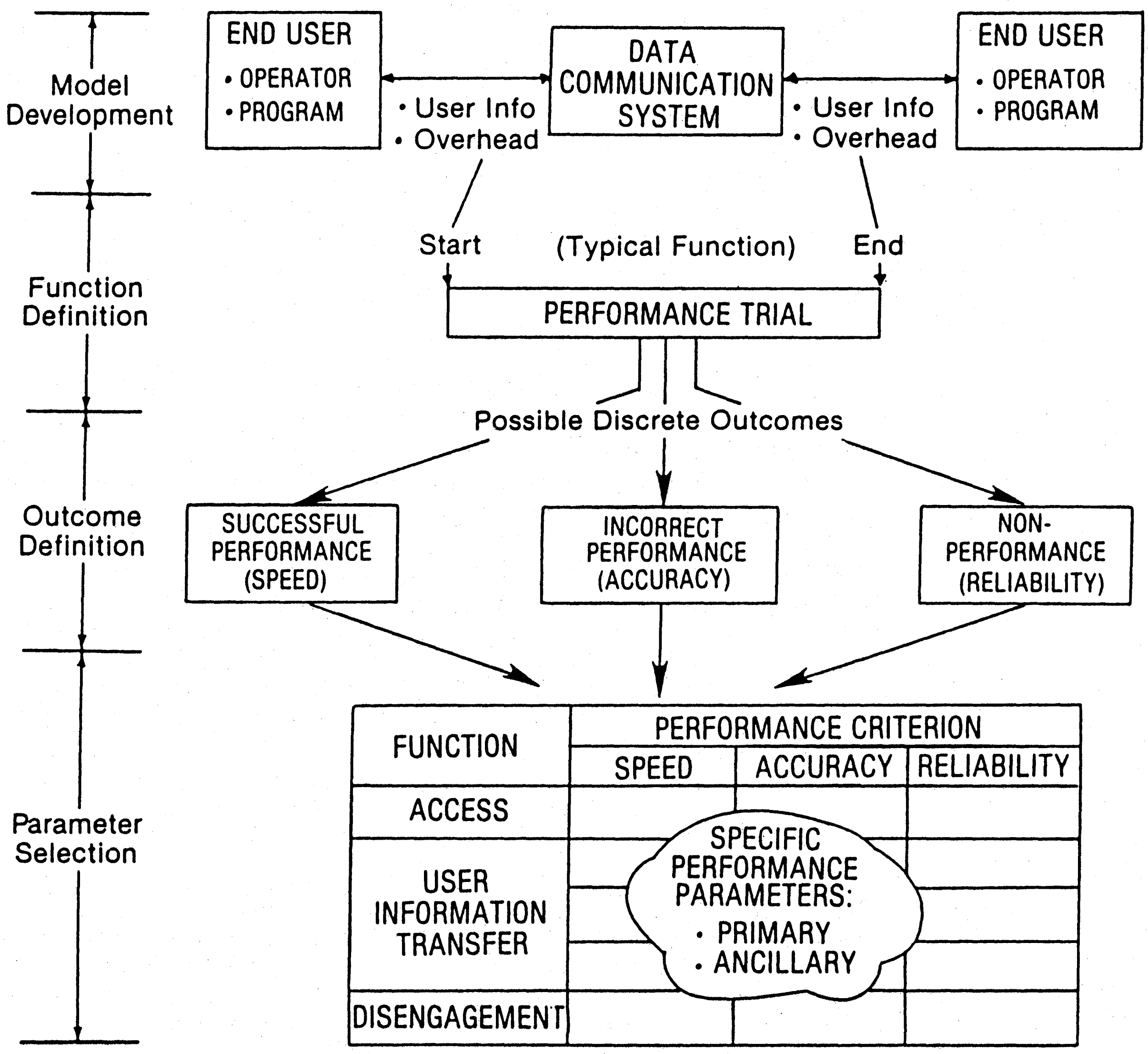


Figure A-1. Summary of ANS X3.102 parameter development process.

that is applicable to all data communication systems and services, regardless of differences such as transmission media, network topologies, and protocols.

A.1.1 End Users

The model defines the end user of a data communication system or service as one of the following:

- The human operator of a data terminal (e.g., a person operating an automated banking terminal) or

- a computer application program that processes communicated information (e.g., a COBOL program that calculates payroll information based on employee records stored in a remote data base).

An end user may employ data storage media to transfer information to or receive information from a system. Typical media used by terminal operators include punched cards and printed pages; typical media used by application programs are magnetic tapes and disks. In all cases where such media are employed, they are associated with the user rather than the system.

A.1.2 Data Communication System

In the ANS X3.102 model, a data communication system includes all functional and physical elements (e.g., transmission facilities, switches, data terminals, and protocols) that participate to provide data communication service between end users.

A.1.3 User/System Interface

A user/system interface is defined as any physical or functional boundary between an end user and a data communication system. Four types of user/system interfaces are distinguished by the model; these are illustrated in Figure A-2:

- When the end user is a human terminal operator without a data medium, the user/system interface is the physical interface between the operator and the data terminal (Figure A-2a).

- When the end user is a human terminal operator with a data medium, the user/system interface includes both the physical interface between the operator and the data terminal, and the physical interface between the medium and its input/output terminal (Figure A-2b).

- When the end user is an application program without a data medium, the user/system interface is the functional interface

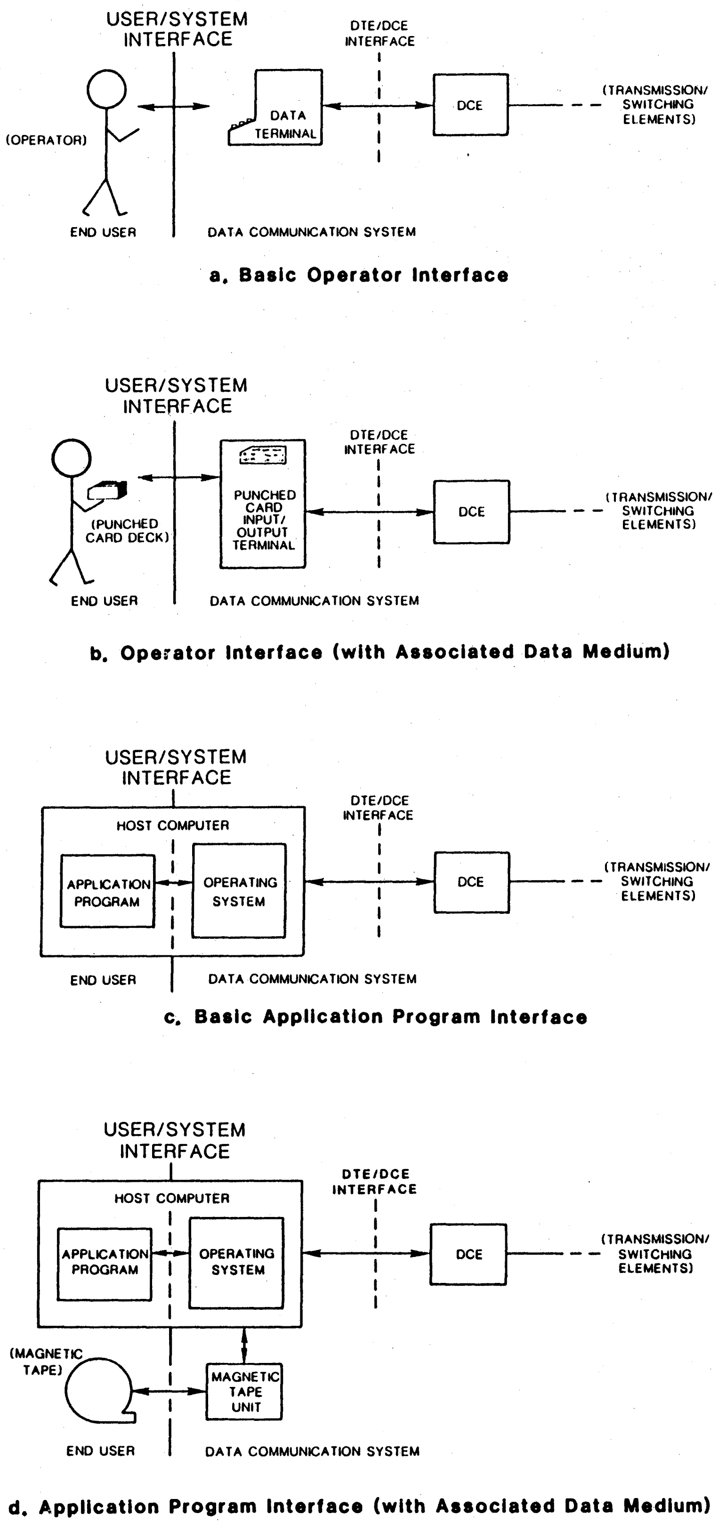


Figure A-2. Principal types of user/system interfaces.

between the program and the local operating system or communication access program (Figure A-2c).

- When the end user is an application program with a data medium, the user/system interface includes both the preceding functional interface and the physical interface between the medium and its input/output terminal (Figure A-2d).

A.1.4 Transferred Information

The ANS X3.102 model divides all transferred information into two categories. User information consists of all information that is input to the system by a user (called the source user) with the intent that it be delivered to another user (called the destination user). Overhead information consists of all other transferred information. The latter includes

- information transferred from a user to the system for the purpose of controlling internal system operations rather than for delivery to another user (e.g., ESC and ENQ characters, off-hook and on-hook signals),
- information generated within the system and transferred to a user for the purpose of reporting system status or controlling user activities (e.g., circuit busy signals), and
- information that is neither input from nor output to a user, but is transferred between distinct elements of a system to coordinate their operation (e.g., SYN, ACK, and NAK characters).

A.1.5 Interface Events

Any discrete transfer of user or overhead information across a user/system interface is called an interface event. Typical events at an operator/terminal interface include typing and printing. Typical events at an interface between an application program and an operating system include issuing system calls and setting and clearing flags. Typical events at a medium/terminal interface include reading punched cards and writing magnetic tape.

A.1.6 Data Communication Session

A data communication session is defined by ANS X3.102 as a coordinated sequence of user and system activities whose purpose is to transfer user information from one or more source users to one or more destination users. A normal data communication session between a user pair consists of

- access activities, which produce the conditions that enable the system to accept source user information for transfer to a destination user (e.g., establishing physical circuits and X.25 virtual circuits),

- user information transfer activities, which accomplish the transfer of user information from the source to the destination user (e.g., formatting, transmission, storage, and error control), and

- disengagement activities, which terminate the conditions that enabled the transfer of user information (e.g., disconnecting physical circuits and clearing X.25 virtual circuits).

The nature and sequence of interface events that occur in a data communication session are system and application dependent. A typical session begins with an interface signal issued by a user (called the originating user) requesting data communication service and committing that user to participate in the session (e.g., typing a Connect request at an operator terminal). The final interface event in a session verifies that the involvement of the last participating user has been terminated (e.g., printing a Closed message at an operator terminal). The period of involvement in a particular session may differ for each user.

The standard divides data communication sessions into two categories. In connection-oriented sessions, user information is entered only after the nonoriginating user (the user not initiating a data communication session) has been contacted and committed to participate in the session (e.g., sessions associated with traditional circuit-switched and modern virtual circuit services). In connectionless sessions, all user information can be entered before the commitment of the nonoriginating user (e.g., sessions associated with traditional message-switched and modern datagram services).

A.2 Function Definition

Any useful description of performance must refer to some particular function. The second step in developing the ANS X3.102 performance parameters was to identify a set of primary data communication functions to serve as the basis of performance description. Access, user information transfer, and disengagement were selected for this purpose.

In the user-oriented approach followed by ANS X3.102, each primary function is characterized by beginning and ending events that can be observed at a user/system interface. System-specific interface events are not suitable for this. Instead, the standard specifies more general system-independent reference events, each of which subsumes a variety of system-specific interface events having a common performance significance.

As an illustration of the reference event concept, all interface signals issued for the purpose of initiating a data communication session are represented by a single Access Request reference event. This reference event corresponds to the beginning of the access function. Examples of Access Request events include issuing the off-hook signal in the public telephone system and typing a Connect request in the ARPANET.

The primary data communication functions are characterized in terms of reference events as described in the following paragraphs.

A.2.1 Access

The access function begins with the issuance of an Access Request signal (discussed previously) at the interface between a user and the data communication system. It ends when the first bit (i.e., the start of the first block) of source user information is entered (after connection is established in a connection-oriented session).

A.2.2 User Information Transfer

The user information transfer function begins when the access function ends. It ends when the final Disengagement Request signal (discussed below) is issued in a data communication session.

To provide a more detailed description of user information transfer performance, ANS X3.102 defines a bit transfer function and a block transfer function. Each function begins when the corresponding user information unit (bit or block) has entered the system and its delivery to the destination user has been authorized. Each function ends when delivery of the corresponding user information unit to the destination user has been completed (with appropriate notification of that user if required). The standard defines a user information block as a set of contiguous user information bits that are delimited at a source user/system interface and intended for transfer as a unit to a destination user. While the block transfer function is usually more relevant, the bit transfer function is often useful for comparing performance when different block lengths are employed.

A.2.3 Disengagement

The disengagement function associated with a particular user in a data communication session begins with the issuance of a Disengagement Request for that user. A Disengagement Request is a reference event that represents any interface signal issued for the purpose of terminating a user's participation in an established data communication session. Examples include the on-hook signal in the public telephone network and the Close request (after successful access) in the ARPANET. Depending on system characteristics, the Disengagement Request for an end user may be issued by that user, by the other user participating in the data communication session, or by the system.

The disengagement function for a particular user ends when that user is able to initiate a new access attempt. Most data communication systems notify the user that a new session may be initiated by issuing an explicit interface signal (e.g., printing a Closed message at an operator terminal in the ARPANET). All such signals are represented by the Disengagement Confirmation reference event. In systems where no such notification is provided, the user may issue a new Access Request to confirm disengagement. A separate disengagement function is associated with each user in a data communication session.

For simplicity, the function definitions given above strictly apply to a data communication session involving a single pair of users. The same concepts may be applied to sessions involving multiple user pairs by defining

- o an access function for each independent connection between an originating and nonoriginating user,
- o separate bit and block transfer functions for each source/destination user pair, and
- o a separate disengagement function for each user.

A.3 Outcome Definition

The third step in developing the ANS X3.102 performance parameters was to identify, for each of the primary data communication functions, a set of possible outcomes that may occur in a performance trial. The outcomes are grouped into three categories:

- o Successful Performance. The function is completed within the maximum performance time, and the result is as intended.

- Incorrect Performance. The function is completed within the maximum performance time, but the result is not as intended.

- Nonperformance. The function is not completed within the maximum performance time.

These categories closely correspond to the performance criteria that most frequently concern end users: speed (delay or rate), accuracy, and reliability. Familiar examples in each category are provided by the public telephone network: connection to the called party (successful performance), connection to a "wrong number" caused by a system switching error (incorrect performance), and the system's blocking of a call attempt as indicated by a "circuit busy" signal (nonperformance).

Maximum performance times are associated with the access, block transfer, and disengagement functions; they are defined by ANS X3.102 as three times the specified performance time. The latter times are provided (in any particular application) by users of the standard and generally represent user requirements or are average values derived from previous measurements. A performance timeout occurs when a trial does not end within the maximum performance time. Performance timeout is a special case of nonperformance.

To provide a more detailed description of performance, ANS X3.102 separates incorrect performance into various function-specific outcomes and separates nonperformance into two outcomes, based on the entity (the system or a user) responsible for the failure. Outcomes that are attributable to user nonperformance are excluded from measurement samples used to estimate values of ANS X3.102 performance parameters.

To assess responsibility for a timeout failure, the performance period for the primary function is divided into alternating intervals of system and user responsibility by observing which entity must produce the next interface event. The fraction of the total performance time for which users are responsible is then calculated and compared with a "specified user fraction of performance time" for the function. If the measured fraction exceeds the specified value, responsibility for the excessive delay is assigned to the user. Otherwise, that responsibility is assigned to the system. Like the specified performance time discussed earlier, the specified user fraction of performance time is provided (in any particular application) by users of the standard; it normally represents an average value derived from previous measurements. Procedures for allocating performance time to users or the system are developed in the companion measurement standard, ANS X3.141.

The outcomes defined by ANS X3.102 for each primary data communication function are summarized in Table A-1. The following paragraphs provide additional details.

A.3.1 Access

In connection-oriented sessions, Successful Access is distinguished from Incorrect Access by the requirement that the intended nonoriginating user must be contacted and committed to participate in the session prior to the start of user information transfer. This commitment corresponds to the Nonoriginating User Commitment reference event, which represents any interface signal that indicates the (called) user's willingness to participate in a requested data communication session.

Incorrect Access is essentially a "wrong number." It occurs when the system establishes a physical or logical connection to a user not intended by the originator of the session and does not correct the error before the start of user information transfer. Because the system does not establish a connection between users in a connectionless session, Incorrect Access can occur only in connection-oriented sessions.

Access Denial may occur in two ways:

- o a System Blocking Signal is issued within the maximum access performance time, terminating the access attempt, and
- o some other system response to an Access Request occurs within the maximum performance time, but excessive delay by the system in performing actions required to complete the access attempt results in access timeout.

A System Blocking Signal is a reference event that represents any interface signal issued by the system during an access attempt to notify the originating user that the system cannot provide a requested data communication service because some system facility (e.g., a trunk circuit) is not available. A familiar example cited earlier is the two-cycle-per-second "circuit busy" signal in the public telephone network.

The Access Outage outcome essentially implies a "dead" system (e.g., a telephone system that fails to provide dial tone for an extended period). It is distinguished from Access Denial because the appropriate user actions in the two cases frequently differ. If Access Denial occurs, the user can generally

Table A-1. Summary of Performance Trial Outcomes

PRIMARY FUNCTION \ OUTCOME CATEGORY	SUCCESSFUL PERFORMANCE	INCORRECT PERFORMANCE	NONPERFORMANCE: SYSTEM NONPERFORMANCE	NONPERFORMANCE: USER NONPERFORMANCE
ACCESS	**SUCCESSFUL ACCESS.** USER INFORMATION TRANSFER BEGINS (I.E., AT LEAST ONE BIT OF SOURCE USER INFORMATION IS INPUT TO THE SYSTEM) WITHIN THE MAXIMUM ACCESS PERFORMANCE TIME. IN A CONNECTION-ORIENTED SESSION, THE INTENDED NONORIGINATING USER MUST BE COMMITTED TO THE SESSION PRIOR TO THE START OF TRANSFER.	**INCORRECT ACCESS.** USER INFORMATION TRANSFER BEGINS (IN A CONNECTION-ORIENTED SESSION) WITHIN THE MAXIMUM ACCESS PERFORMANCE TIME, BUT THE TRANSFER IS TO AN UNINTENDED DESTINATION USER.	**ACCESS DENIAL.** THE SYSTEM ISSUES AN INTERFACE SIGNAL WITHIN THE MAXIMUM ACCESS PERFORMANCE TIME, BUT THE ACCESS ATTEMPT FAILS AS A RESULT OF THE ISSUANCE OF A BLOCKING SIGNAL OR EXCESSIVE DELAY BY THE SYSTEM. **ACCESS OUTAGE.** THE SYSTEM FAILS TO ISSUE ANY INTERFACE SIGNAL WITHIN THE MAXIMUM ACCESS PERFORMANCE TIME.	**USER BLOCKING.** THE ACCESS ATTEMPT FAILS AS A RESULT OF THE ISSUANCE OF A BLOCKING SIGNAL OR EXCESSIVE DELAY BY A USER.
USER INFORMATION TRANSFER: BIT TRANSFER	**SUCCESSFUL BIT TRANSFER.** A TRANSMITTED BIT IS DELIVERED TO THE INTENDED DESTINATION USER WITHIN THE MAXIMUM PERFORMANCE TIME FOR THE ASSOCIATED BLOCK, AND THE CONTENT OF THE DELIVERED BIT IS CORRECT.	**INCORRECT BIT.** A TRANSMITTED BIT IS DELIVERED TO THE INTENDED DESTINATION USER WITHIN THE MAXIMUM PERFORMANCE TIME FOR THE ASSOCIATED BLOCK, BUT THE CONTENT OF THE DELIVERED BIT IS INCORRECT. **MISDELIVERED BIT.** A BIT TRANSFERRED FROM A SOURCE USER TO A PARTICULAR DESTINATION USER WAS INTENDED FOR DELIVERY TO SOME OTHER USER. **EXTRA BIT.** A BIT RECEIVED BY THE DESTINATION USER IN A PARTICULAR DATA COMMUNICATION SESSION WAS NOT OUTPUT BY THE SOURCE USER IN THAT SESSION.	**LOST BIT.** A TRANSMITTED BIT IS NOT DELIVERED TO THE INTENDED DESTINATION USER WITHIN THE MAXIMUM PERFORMANCE TIME FOR THE ASSOCIATED BLOCK, AND THE SYSTEM IS RESPONSIBLE FOR THE FAILURE.	**REFUSED BIT.** A TRANSMITTED BIT IS NOT DELIVERED TO THE INTENDED DESTINATION USER WITHIN THE MAXIMUM PERFORMANCE TIME FOR THE ASSOCIATED BLOCK, AND A USER IS RESPONSIBLE FOR THE FAILURE.
USER INFORMATION TRANSFER: BLOCK TRANSFER	**SUCCESSFUL BLOCK TRANSFER.** A TRANSMITTED BLOCK IS DELIVERED TO THE INTENDED DESTINATION USER WITHIN THE MAXIMUM BLOCK TRANSFER PERFORMANCE TIME, AND THE CONTENT OF THE DELIVERED BLOCK IS CORRECT.	**INCORRECT BLOCK.** AT LEAST SOME OF THE BITS IN A TRANSMITTED BLOCK ARE DELIVERED TO THE INTENDED DESTINATION USER WITHIN THE MAXIMUM BLOCK TRANSFER PERFORMANCE TIME, BUT THE CONTENT OF THE DELIVERED BLOCK IS INCORRECT. **MISDELIVERED BLOCK.** A BLOCK TRANSFERRED FROM A SOURCE USER TO A PARTICULAR DESTINATION USER INCLUDES ONE OR MORE BITS INTENDED FOR DELIVERY TO SOME OTHER USER (I.E., THE TRANSFERRED BLOCK INCLUDES ONE OR MORE MISDELIVERED BITS). **EXTRA BLOCK.** NONE OF THE BITS IN A BLOCK RECEIVED BY THE DESTINATION USER IN A PARTICULAR DATA COMMUNICATION SESSION WERE OUTPUT BY THE SOURCE USER IN THAT SESSION (I.E., THE RECEIVED BLOCK INCLUDES ONLY EXTRA BITS).	**LOST BLOCK.** NONE OF THE BITS IN A TRANSMITTED BLOCK ARE DELIVERED TO THE INTENDED DESTINATION USER WITHIN THE MAXIMUM BLOCK TRANSFER PERFORMANCE TIME, AND THE SYSTEM IS RESPONSIBLE FOR THE FAILURE.	**REFUSED BLOCK.** NONE OF THE BITS IN A TRANSMITTED BLOCK ARE DELIVERED TO THE INTENDED DESTINATION USER WITHIN THE MAXIMUM BLOCK TRANSFER PERFORMANCE TIME, AND A USER IS RESPONSIBLE FOR THE FAILURE.
DISENGAGEMENT	**SUCCESSFUL DISENGAGEMENT.** THE DISENGAGING USER IS FREED TO INITIATE A NEW DATA COMMUNICATION SESSION WITHIN THE MAXIMUM DISENGAGEMENT PERFORMANCE TIME.		**DISENGAGEMENT DENIAL.** THE DISENGAGING USER IS NOT FREED TO INITIATE A NEW DATA COMMUNICATION SESSION WITHIN THE MAXIMUM DISENGAGEMENT PERFORMANCE TIME, AND THE SYSTEM IS RESPONSIBLE FOR THE FAILURE.	**USER DISENGAGEMENT BLOCKING.** THE DISENGAGING USER IS NOT FREED TO INITIATE A NEW DATA COMMUNICATION SESSION WITHIN THE MAXIMUM DISENGAGEMENT PERFORMANCE TIME, AND A USER IS RESPONSIBLE FOR THE FAILURE.

obtain service on a subsequent access attempt. Access Outage, on the other hand, often indicates the need for maintenance.

User Blocking can also occur in two ways:

- a User Blocking Signal is issued within the maximum access performance time, terminating the access attempt, and
- a system response to an Access Request occurs within the maximum performance time, but excessive delay by a user in performing actions required to complete the access attempt results in access timeout.

A User Blocking Signal is the user counterpart to a System Blocking Signal, and represents any interface signal indicating that the issuing user will not participate in a requested data communication session. An example in the public telephone network occurs when a calling user replaces the handset on-hook during connection.

A.3.2 User Information Transfer

Extra Bit outcomes may result from the (erroneous) duplication of data input to the system by the source user, or they may represent data generated or misdelivered by the system. Because Misdelivered Bit/Block outcomes are difficult to identify in most practical measurements, misdelivery performance assessment is regarded as optional in ANS X3.102. When they are not distinguished, Misdelivered Bit/Block outcomes are counted as Extra Bit/Block outcomes.

A.3.3 Disengagement

User Disengagement Blocking can occur in two ways:

- a disengagement blocking signal is issued by a user within the maximum performance time, preventing the termination of a connection-oriented data communication session, and
- excessive delay by a user in performing actions required to complete the disengagement attempt results in disengagement timeout.

An example of a disengagement blocking signal is the case where one user issues a Close request and the other user refuses that request in order to transmit additional data.

No disengagement outcome in the incorrect performance category is defined by ANS X3.102.

A.4 Parameter Selection

The final step in developing the ANS X3.102 parameters was to select and define a set of parameters that describes performance relative to the function outcomes. Table A-2 summarizes the selected performance parameters, which are grouped into two categories:

- o primary parameters, which describe the joint performance of users and the system, and
- o ancillary parameters, which describe the influence of user delay on values of the primary speed parameters.

A.4.1 Primary Parameters

With certain exceptions, a primary parameter corresponds to each of the function outcomes specified by the standard (Table A-1). Time (delay or speed) parameters are associated with successful performance outcomes for the access, block transfer, and disengagement functions. Each delay parameter expresses the average performance time required to complete the corresponding function for trials that result in successful performance. A delay parameter is not defined for the bit transfer function, since it would be identical to Block Transfer Time for many buffered systems and would often be difficult to measure in other cases. Failure probability (accuracy and reliability) parameters are associated with all incorrect performance and system nonperformance outcomes. Each of these parameters expresses the conditional probability of observing the corresponding failure on any given performance trial that does not result in user nonperformance. No parameters correspond to user nonperformance outcomes, since (as indicated previously) trials resulting in these outcomes are not included in the description of performance specified by ANS X3.102.

In addition to the parameters that correspond to specified outcomes, the selected primary parameters include User Information Bit Transfer Rate (to describe throughput) and Transfer Denial Probability (to describe system unavailability). Both of these parameters involve the concept of a transfer sample, an observation of user information transfer performance between a particular pair of source and destination users. A transfer sample contains a specified number of successive bit transfer outcomes within a data communication session and includes at least one interblock gap. To facilitate measurement, transfer samples normally begin and end on block boundaries. The

Table A-2. Summary of ANS X3.102 Performance Parameters

FUNCTION	PERFORMANCE CRITERION: SPEED	PERFORMANCE CRITERION: ACCURACY	PERFORMANCE CRITERION: RELIABILITY	PERFORMANCE TIME ALLOCATION
ACCESS	ACCESS TIME	INCORRECT ACCESS PROBABILITY	ACCESS DENIAL PROBABILITY ACCESS OUTAGE PROBABILITY	USER FRACTION OF ACCESS TIME
USER INFORMATION TRANSFER	BLOCK TRANSFER TIME	BIT ERROR PROBABILITY BIT MISDELIVERY PROBABILITY EXTRA BIT PROBABILITY	BIT LOSS PROBABILITY	USER FRACTION OF BLOCK TRANSFER TIME
		BLOCK ERROR PROBABILITY BLOCK MISDELIVERY PROBABILITY EXTRA BLOCK PROBABILITY	BLOCK LOSS PROBABILITY	
	USER INFORMATION BIT TRANSFER RATE	TRANSFER DENIAL PROBABILITY		USER FRACTION OF INPUT/OUTPUT TIME
DISENGAGEMENT	DISENGAGEMENT TIME	DISENGAGEMENT DENIAL PROBABILITY		USER FRACTION OF DISENGAGEMENT TIME

Legend:
- (blank box) Primary Parameters
- (hatched box) Ancillary Parameters

The Performance Time Allocation column is hatched (Ancillary Parameters); the other cells are blank (Primary Parameters).

input function for a transfer sample begins with the input of the first user information block included in the sample, and ends when the last user information bit included in the sample has entered the system and its transfer to the destination user has been authorized. The output function for a transfer sample is delimited (at the destination user/system interface) by the counterparts of the source events that bound the input function. A transfer sample is characterized by the associated input and output performance times, and by the outcomes of the bit transfer attempts included in the sample.

The User Information Bit Transfer Rate for a transfer sample is the number of Successful Bit Transfer outcomes in the sample divided by the larger of the sample input or output time. An equivalent long-term average rate may be obtained by concatenating many successive transfer samples. User Information Bit Transfer Rate is, thus, the slower of two rates--the rate at which user information is transferred from a source user to the system, or the rate at which the same user information is transferred from the system to the destination user.

The performance observed in a transfer sample is compared with a specified "threshold of acceptability" for each of four "supported" user information transfer performance parameters: Bit Error Probability, Bit Loss Probability, Extra Bit Probability, and User Information Bit Transfer Rate. If the observed performance is equal to or better than the threshold of acceptability for each of the supported parameters, the outcome of the transfer sample is defined to be Successful Transfer. If the observed performance is worse than the threshold of acceptability for one or more supported parameters, the outcome is defined to be Transfer Denial when the failure is attributable to the system and Rejected Sample when the failure is attributable to the users. Transfer Denial Probability is the conditional probability of observing a Transfer Denial outcome for any given transfer sample that does not result in a Rejected Sample (i.e., in user nonperformance). Transfer Denial Probability provides an estimate of system unavailability (the complement of availability).

ANS X3.102 indirectly specifies the size of a transfer sample by stipulating that it must be sufficiently large to enable each of the supported failure probability parameters to be estimated at its threshold value with a relative precision of at least 50% at the 95% confidence level. The minimum size thus depends on the specified acceptability thresholds; in most cases, a transfer sample containing a few thousand bit transfer attempts will suffice.

Procedures for determining the size of such a sample are described by Miles (1984).

In a Transfer Denial measurement, the threshold of acceptability for each of the supported bit transfer failure probabilities is defined by ANS X3.102 as the fourth root of the "specified value" for the particular parameter. The threshold for the User Information Bit Transfer Rate is one-third of the corresponding "specified value." Like other specified parameter values discussed earlier, specified values for Transfer Denial assessment are provided (in any particular application) by users of the standard and generally represent user requirements or are average values derived from previous measurements.

A.4.2 Ancillary Parameters

The successful completion of a primary data communication function generally requires the performance of intermediate activities by an end user. User delays in carrying out such activities may, therefore, significantly affect the performance time for completing the function. To quantitatively describe the influence of user delay on values of the primary speed parameters, ANS X3.102 defines a set of four ancillary parameters. The ancillary parameter associated with a particular function expresses the average proportion of the total performance time (for trials that result in successful performance) that is attributable to user delay. The ancillary parameter definitions are based on the same concept that underlies the assessment of responsibility for timeout failures--that the performance period for a function can be divided into alternating intervals of system and user responsibility.

A.5 References

ANSI (1983), American National Standard for Information Systems - Data communication systems and services - user-oriented performance parameters, ANSI X3.102-1983. (American National Standards Institute, Inc., New York, NY).

Miles, M. J. (1984), Sample size and precision in communication performance measurement, NTIA Report 83-153, August (NTIS Order Number PB 85-114270).

APPENDIX B: SUMMARY OF AMERICAN NATIONAL STANDARD X3.141

This appendix summarizes American National Standard X3.141, "Data Communication Systems and Services--Measurement Methods for User-Oriented Performance Evaluation" (ANSI, 1987). This standard specifies uniform methods to estimate the performance parameters defined in ANS X3.102. The methods are general and implementation independent, and may be used to estimate performance values at any pair of interfaces connecting a data communication system or subsystem to its users.

Figure B-1 outlines the performance measurement process specified in ANS X3.141. Inputs to the measurement process consist of

- measurement objectives defined by the context of the experiment and
- digital signals observed at the monitored user/system interfaces.

Results of the measurement process consist of

- estimates of the ANS X3.102 performance parameters and
- related statistics (e.g., confidence limits and histograms).

The measurement process is accomplished in four principal phases:

1. Experiment Design. Measurement objectives are developed into a detailed experiment plan that specifies the performance data to be collected and the conditions of individual tests.
2. Data Extraction. Signals transferred across selected pairs of user/system interfaces are monitored to identify and record reference events needed to estimate a selected set of ANS X3.102 performance parameters.
3. Data Reduction. The recorded reference events are examined to identify individual performance trials and classify their outcomes.
4. Data Analysis. Performance parameter estimates and related conclusions are determined from the reduced performance data.

The subsections that follow describe each phase of the measurement process in greater detail.

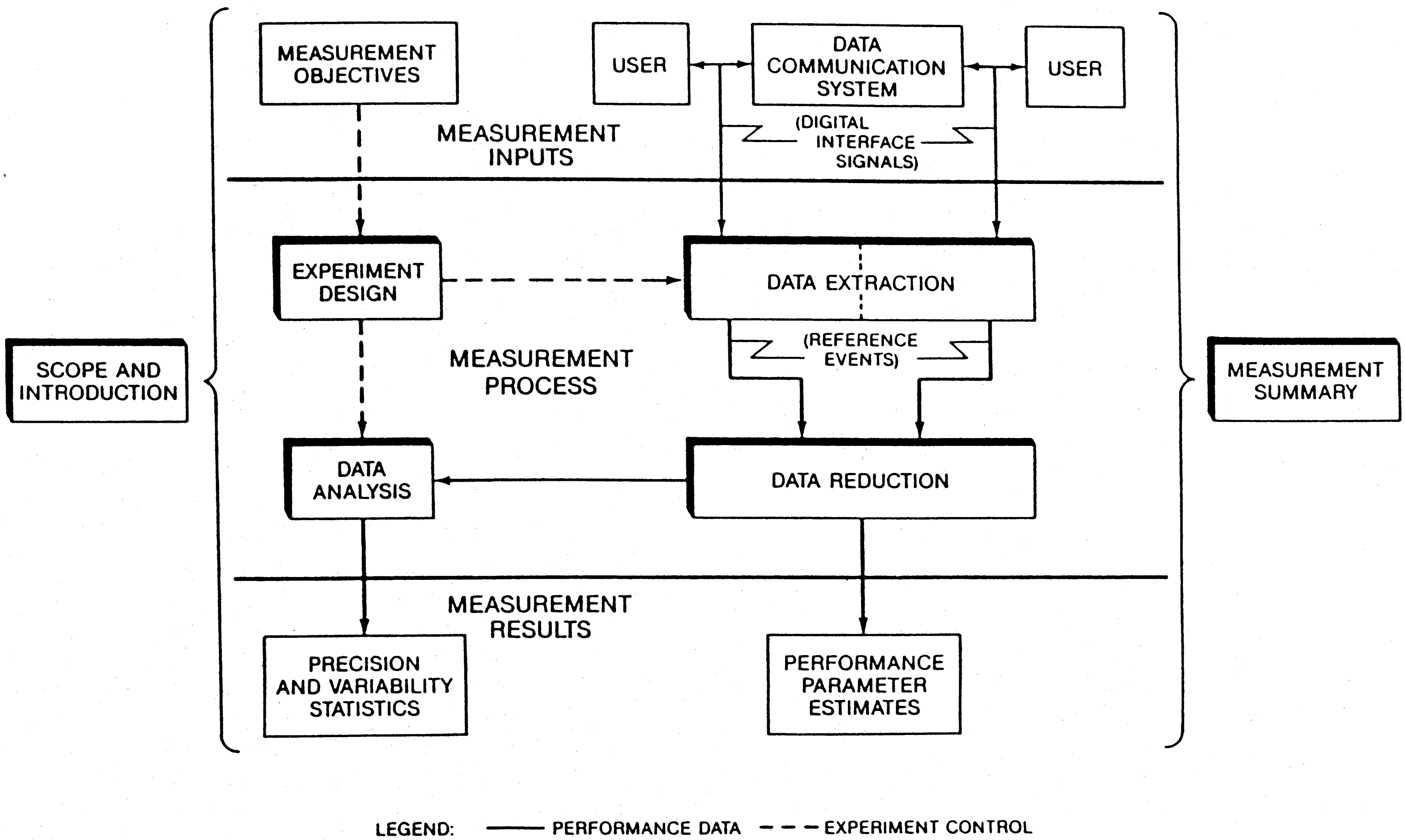


Figure B-1. Summary of the ANS X3.141 measurement process.

B.1 Experiment Design

In the experiment design phase of the ANS X3.141 measurement process, overall objectives are developed into a detailed experiment plan. The experiment is designed to achieve

- explicitly stated precision and the absence of bias in the measured values (accuracy),
- clearly defined applicability of measurement results, and
- efficient use of resources.

The standard defines a seven-step procedure for the design of performance measurement experiments. These steps are outlined in the following paragraphs.

B.1.1 Experiment Objectives

Define the objectives of the experiment in the context in which the results will be used. Three types of performance measurement experiments may be conducted using the guidelines presented in ANS X3.141.

Performance characterization experiments estimate performance parameters under a single combination of factor levels (a fixed set of test conditions). Their results are most commonly used in decisions involving user activities or facilities where system performance is regarded as fixed.

Simple hypothesis test experiments also estimate performance parameters under a single combination of factor levels, but their purpose is to compare the observed values with previously specified values. The results of such experiments are typically binary (e.g., observed performance either does or does not meet a given requirement), and are used in decision-making such as acceptance testing and in network maintenance and control where observed performance is compared with a threshold to identify conditions that require correction.

Analysis of factor effects experiments compare performance measured under different factor level combinations to identify the effects of performance factors. Results of these experiments may be applied to optimization problems related to usage (e.g., selecting a block length to maximize throughput) and network design (e.g., choosing optimum routes).

B.1.2 Measured Parameters

Select the ANS X3.102 parameters to be measured. Depending on the objectives, all or any specified subset of the ANS X3.102 parameters may be measured.

B.1.3 Population Definition

Define the population of performance trials (e.g., access attempts). When applicable, specify

- o characteristics of the user pairs to which the data communication service is provided,
- o the set of user pairs to be represented (as distinguished from the subset actually measured),
- o periods within which performance is to be characterized,
- o characteristics of the user/system interfaces to be monitored, including the placement of the measurement points,
- o the data communication session type,
- o session profiles (or equivalent specifications) defining the event sequences that occur at the monitored interfaces during a typical successful session,
- o service refusal or interruption (e.g., blocking) sequences explicitly allowed by the system design,
- o reference events corresponding to each performance-significant interface event, and
- o thresholds that distinguish successful trials from failures.

B.1.4 Performance Factors

Specify the factors presumed to influence performance, the relevant levels for each factor, and the combinations of factor levels to be tested. The selection of factors, levels, and combinations of factor levels depends on the objectives of the experiment. Factors and levels should be distinguished in an experiment design only if their effects must be determined to achieve experiment objectives. When feasible, each combination of factor levels should be tested at least once (a factorial experiment), and the entire experiment should be replicated to check for the presence of significant factors not specified in the design. When the number of factor level combinations is too large for each to be tested, the selected combinations should include the factor levels whose effects are expected to be most important.

B.1.5 Population Sample

From the defined population of performance trials, select a representative sample of trials to be tested. ANS X3.141 addresses two sample selection issues: the method of selection and the sample size. The trials should, within practical constraints, constitute a random sample of the population (i.e., the trials should be chosen in such a way that each trial in the population has an equal chance of being included in the sample). Practical constraints often result in the selection of nonrandom samples. The most common instance of such a sample is a sequence of successive trials. Once a data extraction arrangement has been established, the usual practice is to observe many consecutive trials before changing the configuration. While this procedure is efficient, the trials are not randomly selected. Dependence that may exist among the successive trials may be accounted for in the statistical analysis of the data (Miles, 1984).

The sample size may be established in either of two ways. It

- may be derived from precision objectives (e.g., by requiring that a delay parameter be estimated to within 0.5 seconds of its true value at the 95% confidence level) or
- it may be based on practical constraints (e.g., data storage capacity, budget, or time).

In experiments where several parameters are to be estimated from a common sample, the sample size should be sufficiently large to achieve the most stringent precision requirement; any less stringent precision requirements will then be achieved as well. The standard does not include procedures for sample size determination, but refers users to those described by Miles (op. cit.) and implemented in an associated computer program. Regardless of how sample sizes are determined, a desired confidence level for the measurement results should normally be specified in the experiment design. The choice of a level depends on the experiment objectives. Confidence levels of 90% or 95% are commonly used.

B.1.6 Test Conditions

Specify the combination of factor levels to be used in each test. The number of possible combinations may be quite large, even in rather small experiments (e.g., 4 factors, each having 3 levels, results in $3^4 = 81$ combinations of levels). In such experiments, the selection of factor level combinations should achieve a favorable balance between two frequently conflicting objectives: measurement accuracy and the efficient use of resources. Maximum accuracy is generally attained by a random assignment of factor level combinations to individual tests. However, the efficient use of resources often imposes constraints that prevent randomization (e.g., it may be difficult to repeatedly vary certain factor levels, such as the city of call origination). According to ANS X3.141, factor level combinations should be assigned to tests as randomly as possible under the constraints of the experiment. Commonly used statistical designs that restrict randomization to accommodate such constraints include randomized blocks, balanced incomplete blocks, and Latin squares (Cox, 1958).

B.1.7 Mathematical Model

Where appropriate, summarize the experiment design in a mathematical model. In the simple mathematical models addressed in the standard, an observed value of a performance parameter (e.g., Block Transfer Time) is expressed as a linear function of

- o the true (but unknown) population value of the performance parameter,
- o observed factor effects, and
- o random errors.

When the factor levels are quantifiable, the factor effects can be described by a linear regression model. The use of mathematical models to describe the measurements is recommended by ANS X3.141, but it is not required.

B.2 Data Extraction

In the data extraction phase of the ANS X3.141 measurement process, signals transferred across selected pairs of user/system interfaces are monitored to identify and record reference events needed to estimate a selected set of ANS X3.102 performance parameters. Data extraction guidelines in

ANS X3.141 specify functional requirements applicable to a single interface monitor--the data extraction element associated with a particular monitored interface. In the most general case, where all 21 parameters defined in ANS X3.102 are evaluated from performance observed at two or more separated interfaces, such a monitor performs three functions:

- Interface Event Collection. Monitor signals transferred across the interface to identify each performance-significant event and determine the time of its occurrence.
- Event Processing. Interpret each significant system-specific event observed at the monitored interface as a system-independent reference event associated with the data communication process model described in ANS X3.102.
- Reference Event Recording. Record the nature and time of occurrence of each observed reference event and (when appropriate) the binary contents of each transferred user information block.

The following paragraphs describe each of these functions in more detail.

B.2.1 Interface Event Collection

The first function of an interface monitor is to observe signals transferred across the interface during a specified measurement period so as to identify each performance-significant event and determine its time of occurrence. An interface event corresponds to a discrete transfer of information across a user/system interface. For the purpose of establishing the time of an interface event, the information is said to have been transferred from a user to the system when

- the information is within the system and
- the system has been authorized to transmit or process it.

Similarly, information is said to have been transferred from the system to a user when

- the information is within the user facility and
- the user has been notified that it is available.

The successful measurement of ANS X3.102 performance parameters requires the synchronization of event-time clocks in geographically remote equipment. The standard does not include procedures for accomplishing this, but it refers users to some practical methods described by Kamas and Howe (1979).

B.2.2 Event Processing

The second function of an interface monitor in an ANS X3.141 performance measurement is to interpret each significant system-specific event observed at the monitored interface as a system-independent reference event associated with the data communication process model described in ANS X3.102. Nine primary reference events are specified, all but one of which (Nonoriginating User Commitment) correspond to the beginning or end of a primary data communication function. These are summarized in Table B-1. The table also presents, for each reference event, a system-specific counterpart that might occur during a data communication session between a terminal operator and a remote application program via a packet-switched network (e.g., the original ARPANET).

In ANS X3.102, the assessment of responsibility for timeout failures and the definitions of ancillary parameters are based on the concept of dividing the performance period for a primary function into intervals of system and user responsibility. To facilitate such a partition, ANS X3.141 defines a set of ancillary reference events. Each of these events describes the effect of a corresponding interface event on user and system responsibility for generating a subsequent interface event. An ancillary event at an interface may affect responsibility at that (local) interface, at the remote interface, or at both interfaces.

At the local interface, occurrence of an ancillary event affects responsibility in one of three ways:

- o the system is given responsibility for generating the next event,
- o the (local) user is given responsibility for generating the next event, or
- o both the user and the system are temporarily relieved of responsibility for generating a subsequent event (since the next event in the normal sequence occurs at the remote interface).

The off-hook action of a calling user illustrates the first effect: the system is given responsibility for issuing a dial tone at the calling interface. The issuance of a dial tone illustrates the second effect: the user is given responsibility for dialing the first digit. An example of the third effect is the issuance of an X.25 Call Request packet. Both the calling user and the system are temporarily relieved of responsibility for generating a

Table B-1. Summary of Primary Reference Events

FUNCTION	REFERENCE EVENT	SYSTEM IMPACT	PERFORMANCE SIGNIFICANCE	ARPANET EXAMPLES
ACCESS	1. ACCESS REQUEST	REQUESTS INITIATION OF DATA COMMUNICATION SESSION AND COMMITS THE ORIGINATING USER TO PARTICIPATE.	BEGINS ACCESS FUNCTION. STARTS THE COUNTING OF ACCESS TIME.	OPERATOR TYPING OF CONNECT REQUEST.
	2. NONORIGINATING USER COMMITMENT	IN A CONNECTION-ORIENTED DATA COMMUNICATION SESSION, INDICATES NONORIGINATING (CALLED) USER WILLINGNESS TO PARTICIPATE.	ELIMINATES INCORRECT ACCESS AS A POSSIBLE ACCESS OUTCOME.	APPLICATION PROGRAM ISSUANCE OF OPEN ANY HOST (LISTEN) SYSTEM CALL.
	3. SYSTEM BLOCKING SIGNAL	NOTIFIES ORIGINATING USER THAT THE SYSTEM CANNOT SUPPORT A REQUESTED DATA COMMUNICATION SESSION.	IDENTIFIES ACCESS ATTEMPT OUTCOME AS ACCESS DENIAL.	SYSTEM PRINTING OF NET TROUBLE MESSAGE AT OPERATOR TERMINAL.
	4. USER BLOCKING SIGNAL	NOTIFIES SYSTEM THAT THE ISSUING USER WILL NOT SUPPORT A REQUESTED DATA COMMUNICATION SESSION.	IDENTIFIES ACCESS ATTEMPT OUTCOME AS USER BLOCKING (EXCLUDED FROM SYSTEM PERFORMANCE MEASUREMENT.)	OPERATOR TYPING OF CLOSE REQUEST (DURING ACCESS).
	5. START OF BLOCK INPUT TO SYSTEM	TRANSFERS ONE OR MORE BITS AT BEGINNING OF USER INFORMATION BLOCK FROM SOURCE USER TO SYSTEM.	WHEN BLOCK IS THE FIRST BLOCK IN A DATA COMMUNICATION SESSION (AFTER NONORIGINATING USER COMMITMENT IN CONNECTION-ORIENTED SESSIONS), COMPLETES ACCESS FUNCTION AND BEGINS USER INFORMATION TRANSFER. STOPS THE COUNTING OF ACCESS TIME.	OPERATOR TYPING OF FIRST USER INFORMATION CHARACTER AT A BUFFERED CRT TERMINAL.
USER INFORMATION TRANSFER	6. START OF BLOCK TRANSFER	AUTHORIZES THE SYSTEM TO TRANSMIT A GIVEN USER INFORMATION BLOCK.	(1) BEGINS BLOCK TRANSFER FUNCTION AND STARTS THE COUNTING OF BLOCK TRANSFER TIME. (2) WHEN BLOCK PRECEDES THE FIRST BLOCK IN A TRANSFER SAMPLE, BEGINS COLLECTION OF THE SAMPLE AND STARTS THE COUNTING OF SAMPLE INPUT TIME. (3) WHEN BLOCK IS THE LAST BLOCK IN A TRANSFER SAMPLE, COMPLETES INPUT OF SAMPLE AND STOPS THE COUNTING OF SAMPLE INPUT TIME.	OPERATOR TYPING OF ANY USER INFORMATION CHARACTER AT AN UNBUFFERED SOURCE TERMINAL. TYPING OF CARRIAGE RETURN AT A BUFFERED SOURCE TERMINAL.
	7. END OF BLOCK TRANSFER	TRANSFERS A GIVEN USER INFORMATION BLOCK TO THE DESTINATION USER, WITH APPROPRIATE NOTIFICATION TO THAT USER WHERE REQUIRED.	(1) COMPLETES BLOCK TRANSFER FUNCTION AND STOPS THE COUNTING OF BLOCK TRANSFER TIME. (2) WHEN BLOCK PRECEDES THE FIRST BLOCK IN A TRANSFER SAMPLE, BEGINS OUTPUT OF THE SAMPLE AND STARTS THE COUNTING OF SAMPLE OUTPUT TIME. (3) WHEN BLOCK IS THE LAST BLOCK IN A TRANSFER SAMPLE, COMPLETES COLLECTION OF THE SAMPLE AND STOPS THE COUNTING OF SAMPLE OUTPUT TIME.	SYSTEM PRINTING OR DISPLAY OF COMPLETE SOURCE USER INFORMATION BLOCK AT THE DESTINATION TERMINAL.
DISENGAGEMENT	8. DISENGAGEMENT REQUEST	REQUESTS TERMINATION OF A USER'S PARTICIPATION IN A DATA COMMUNICATION SESSION.	BEGINS DISENGAGEMENT FUNCTION. STARTS THE COUNTING OF DISENGAGEMENT TIME.	OPERATOR TYPING OF CLOSE REQUEST (AFTER SUCCESSFUL ACCESS).
	9. DISENGAGEMENT CONFIRMATION	CONFIRMS TERMINATION OF A USER'S PARTICIPATION IN A DATA COMMUNICATION SESSION.	COMPLETES DISENGAGEMENT FUNCTION. STOPS THE COUNTING OF DISENGAGEMENT TIME.	SYSTEM PRINTING OF CLOSE MESSAGE AT OPERATOR TERMINAL.

NOTE: Interface events may have no corresponding primary reference event. Such events may be represented by the primary event number "0" in recording reference event sequences.

subsequent event because the next event in the normal sequence (delivery of the Incoming Call packet) occurs at the remote interface.

Independent of its responsibility effect at the local interface, the occurrence of an ancillary event either

- o has no effect on responsibility for generating the next event at the remote interface or

- o gives the system responsibility for generating the next event at the remote interface.

The latter effect occurs only when responsibility at the remote interface is undefined prior to the ancillary event (i.e., when both remote entities are waiting for an event to occur at the other interface). Issuance of an X.25 Restart Request illustrates the first case. The user's input of an X.25 data packet illustrates the second: it gives the system responsibility for delivering the packet to the destination user.

Combining the three local and the two remote responsibility effects results in six responsibility effects. They correspond to the ancillary events summarized in Table B-2.

An interface event may correspond to a primary reference event, an ancillary reference event, or both a primary and an ancillary reference event. The first case is illustrated by the delivery of a user information block in the absence of flow control: that event corresponds to End of Block Transfer but does not have any responsibility effect. The second case is illustrated by the issuance of a dial tone in the public telephone network: that event transfers responsibility at the calling interface from the system to the user but does not correspond to any primary reference event. The last case is illustrated by the issuance of an X.25 Call Request packet: that event corresponds to an Access Request and (as noted earlier) temporarily relieves both the user and the system of responsibility for generating a subsequent event at the calling interface.

B.2.3 Reference Event Recording

The third function of an ANS X3.141 interface monitor is to <u>record</u>

- o the nature of each primary and ancillary reference event observed at the monitored interface,

- o the time of occurrence of each reference event, and

Table B-2. Summary of Ancillary Reference Events

ANCILLARY EVENT	LOCAL EFFECT	REMOTE EFFECT
1	SYSTEM RESPONSIBLE	NO EFFECT
2	USER RESPONSIBLE	NO EFFECT
3	RESPONSIBILITY UNDEFINED	NO EFFECT
4	SYSTEM RESPONSIBLE	SYSTEM RESPONSIBLE
5	USER RESPONSIBLE	SYSTEM RESPONSIBLE
6	RESPONSIBILITY UNDEFINED	SYSTEM RESPONSIBLE

- the binary contents (when required) of each user information block transferred across the interface.

Binary representations used to encode source user information and decode destination user information may differ when code conversion is performed within the system. In such cases, the source monitor should map transferred user information into the destination code. In measurements designed to assess misdelivery performance, the source interface monitor must also produce a record of all source user information input during the measurement period for delivery to users other than the monitored destination user.

Although ANS X3.141 is primarily intended to measure performance between end user interfaces, it may also be adapted to measure the performance of a <u>data communication subsystem</u>--a group of system elements terminated at digital interfaces. The physical or functional boundaries delimiting such a subsystem are called the <u>subsystem interfaces</u>. Each interface defines a collection of entities outside the subsystem, comprising one or more end users and the data communication system elements that connect those users with the subsystem. Any such collection of entities is regarded as an <u>aggregate user</u> of the subsystem and is treated as a single entity in subsystem performance measurements.

Figure B-2 illustrates a pair of typical subsystem interfaces and the associated aggregate users. In this example, each subsystem interface corresponds to the physical interface between data terminal equipment and data circuit-terminating equipment (i.e., a DTE/DCE interface). The data communication subsystem consists of the two DCEs and the connecting network. The two aggregate users are the DTE combined with the operator on one end and the host computer on the other.

B.3 Data Reduction

In the data reduction phase of an ANS X3.141 performance measurement, reference events observed during the data extraction phase are examined to identify individual performance trials and classify their outcomes. Estimated values for a selected set of ANS X3.102 performance parameters are then calculated from the observed outcomes. Data reduction guidelines in ANS X3.141 specify functional requirements for the most general case, in which

- reduction is performed off-line after all extracted performance data have been recorded and

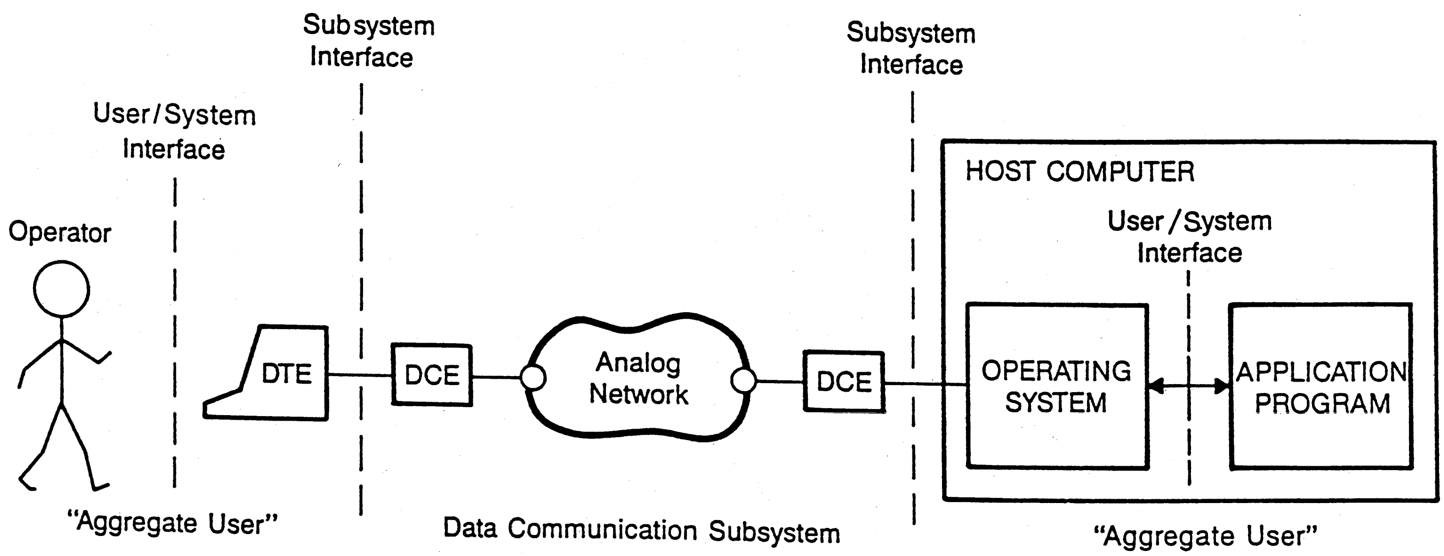


Figure B-2. Typical aggregate users and subsystem interfaces.

- all 21 parameters defined in ANS X3.102 are to be evaluated on the basis of reference events recorded at the monitored interfaces.

The measurement standard includes data reduction specifications for the primary functions. It also specifies a procedure to process ancillary reference events to determine, for an associated primary function, the performance time that is attributable to the user. These specifications are summarized in the paragraphs that follow.

B.3.1 Ancillary Event Consolidation Procedure

Ancillary events recorded by an interface monitor do not always provide a complete history of local responsibility states at the monitored interface because these states can be affected by events at the remote interface. However, the ancillary events recorded by a pair of source and destination interface monitors in a performance measurement jointly contain sufficient information to determine the complete responsibility state history at both interfaces. The production of such a history is a necessary preliminary step in the ANS X3.141 reduction process, and is carried out by an ancillary event consolidation procedure. Local responsibility states determined by the consolidation procedure are derived from the following two rules:

- An ancillary event at an interface determines the subsequent responsibility state at that interface according to the scheme defined in Table B-2--"system responsible," "user responsible," or "responsibility undefined."

- An ancillary event at an interface affects responsibility at the remote interface only if both remote entities (user and system) are waiting for that event (i.e., only if the responsibility state at the remote interface prior to the event is "responsibility undefined"). In all such cases, the responsibility state at the remote interface is changed from "responsibility undefined" to "system responsible."

The consolidated ancillary event history serves as input to a performance time allocation procedure that evaluates user delay associated with the performance of data communication functions. The allocation procedure is described later in this section.

B.3.2 Access Performance Assessment Procedure

As indicated in Figure B-3, the access performance assessment procedure

- o identifies access attempts recorded in a corresponding pair of reference event histories,
- o classifies the outcome of each access attempt, and
- o estimates access performance parameters from the observed outcomes.

The beginning of each access attempt corresponds to an Access Request (reference event 1 in Table B-1). The end of the attempt corresponds to the Start of Block Input to System (i.e., the start of user information transfer), a System Blocking Signal, or a User Blocking Signal (reference events 5, 3, and 4, respectively, in Table B-1). When an access attempt has been identified, the assessment procedure uses criteria defined in ANS X3.102 and summarized in Table A-1 of this report to classify and record the outcome--Successful Access, Incorrect Access, Access Denial, Access Outage, or User Blocking. A logical scheme that implements those criteria is presented in Figure B-4. If access timeout occurs and there is a system response within the maximum access performance time, the assessment procedure assigns responsibility for the excessive delay as outlined in Section A.3. User performance time needed in this determination is obtained from the performance time allocation procedure described later in this section. When all access attempts recorded in the extracted performance data have been identified and classified, the assessment procedure calculates measured values of access performance parameters based on the observed outcomes.

B.3.3 User Information Transfer Performance Assessment Procedure

The user information transfer performance assessment procedure

- o identifies bit and block transfer attempts contained in a corresponding pair of source and destination reference event histories and associated user information records,
- o classifies the outcome of each bit and block transfer attempt identified,
- o selects a sequence of transfer samples to measure Transfer Denial Probability and classifies the outcome of each sample,
- o selects a transfer sample to measure long-term throughput parameters, and

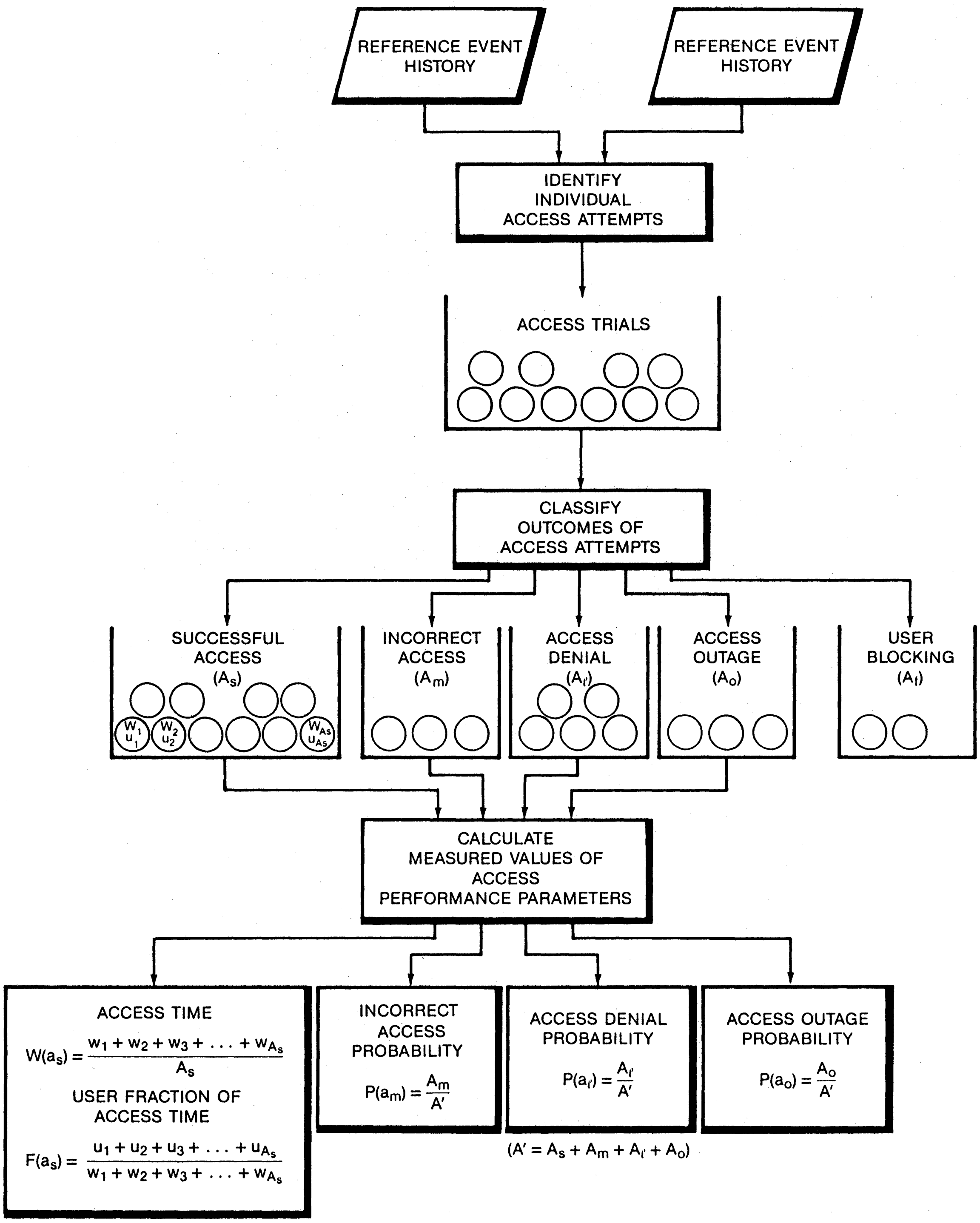


Figure B-3. Outline of access performance assessment.

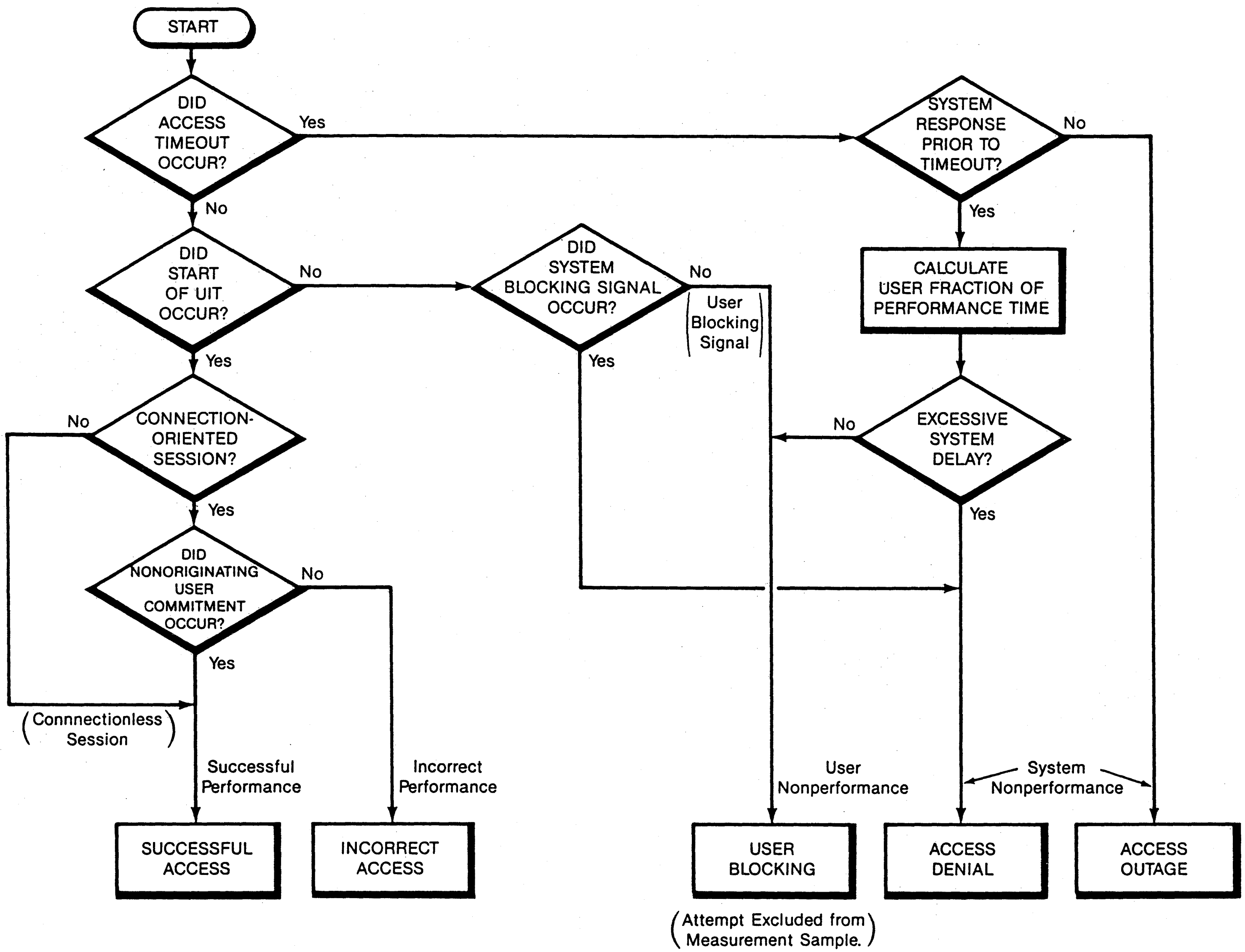


Figure B-4. Scheme for classifying outcomes of access attempts.

- estimates user information transfer performance parameters from the observed outcomes.

The first of these tasks, the identification of bit and block transfer attempts, is accomplished by a <u>data correlator</u> as illustrated schematically in Figure B-5. Input to the correlator consists of corresponding source and destination records of user information transfer events observed at the respective interfaces during a monitored sequence of block transfer attempts. The source record includes the Start of Block Transfer event and the associated binary contents for each block in a sequence of transmitted user information blocks. The destination record includes the End of Block Transfer event and the associated binary contents for each block in the corresponding sequence of received user information blocks. Output from the data correlator consists of records that describe a sequence of block transfer attempts, each of which includes a succession of bit transfer attempts. These correlator output records form the basis for all subsequent tasks in user information transfer performance assessment.

A bit transfer attempt is represented in the user information records by

- a pair of corresponding transmitted and received bits in the source and destination records,

- a transmitted bit in the source record without a counterpart in the destination record, or

- a received bit in the destination record without a counterpart in the source record.

Using the preceding criteria, the data correlator compares source and destination user information records to identify individual bit transfer attempts. Each identified attempt is represented in the correlator output by a <u>bit comparison outcome</u> (BCO) in one of the four following categories:

- <u>Correct BCO</u>. Corresponding bits exist in the source and destination user information records, and their binary values agree.

- <u>Incorrect BCO</u>. Corresponding bits exist in the source and destination user information records, but their binary values differ.

- <u>Undelivered BCO</u>. A bit in the source user information record has no counterpart in the destination user information record.

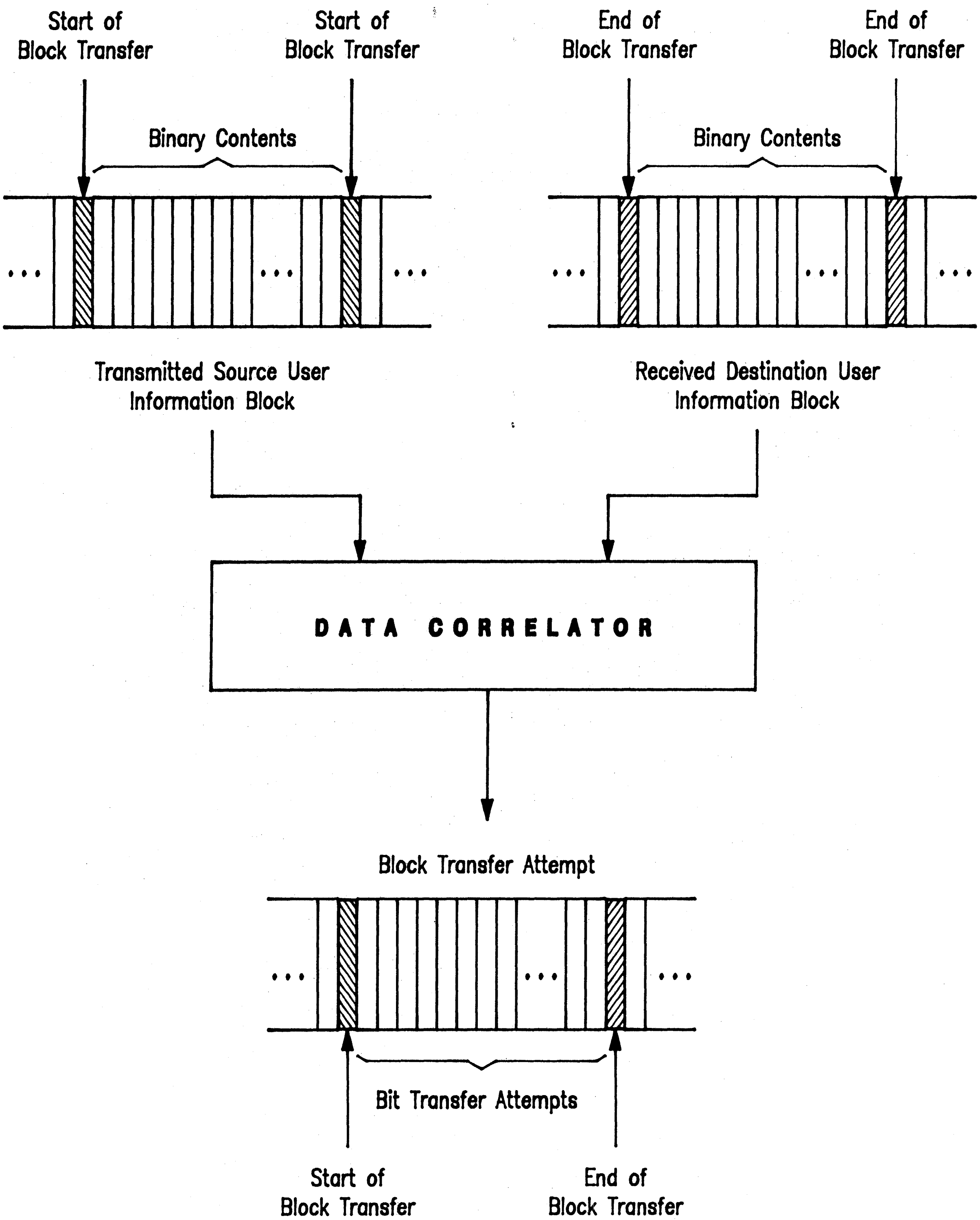


Figure B-5. Outline of data correlation.

- Extra BCO. A bit in the destination user information record has no counterpart in the source user information record.

Examples of data correlator output that illustrate each type of bit comparison outcome are shown in Figure B-6.

A block transfer attempt is represented in the reference event histories by

- a pair of corresponding Start of Block Transfer and End of Block Transfer events in the source and destination histories,

- a Start of Block Transfer event in the source history without a counterpart in the destination history, or

- an End of Block Transfer event in the destination history without a counterpart in the source history.

Using these criteria, the data correlator compares source and destination reference event histories (and the associated user information records) to identify block transfer attempts and the sequence of bit transfer attempts included in each block transfer attempt. A sequence of bit comparison outcomes that corresponds to a given block transfer attempt is called a correlated output block. Detailed procedures for identifying individual bit and block transfer attempts are not defined in ANS X3.141.

The second task in user information transfer performance assessment is classifying the outcomes of bit and block transfer attempts identified by the data correlator. Figure B-7 illustrates a logical scheme that classifies these outcomes in accordance with criteria defined in ANS X3.102 and summarized in Table A-1 of this report. If block transfer timeout occurs, the assessment procedure assigns responsibility for the excessive delay as outlined in Section A.3. User performance time needed in this determination is obtained by using the performance time allocation procedure described later in this section. Refused Block outcomes and the associated Refused Bit outcomes are excluded from samples used to calculate measured values of user information transfer performance parameters. If misdelivery performance assessment is enabled, the assessment procedure compares each Extra Block observed at the monitored destination user interface with blocks that the monitored source user transmitted to the system (during the measurement period) for delivery to other destination users. Any Extra Block that corresponds to a block transmitted to another destination user is reclassified as a Misdelivered Block, and the

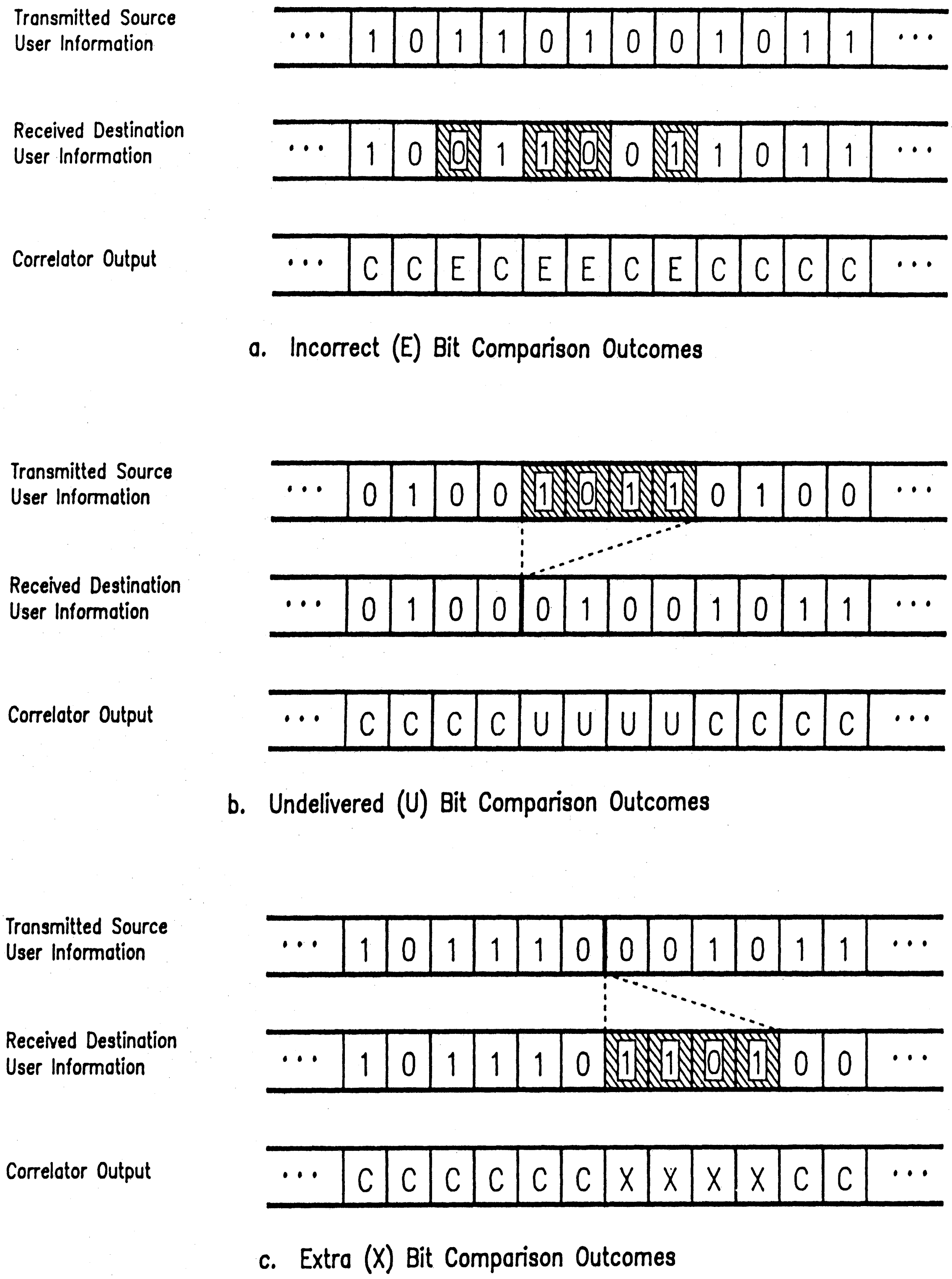


Figure B-6. Examples of data correlator output.

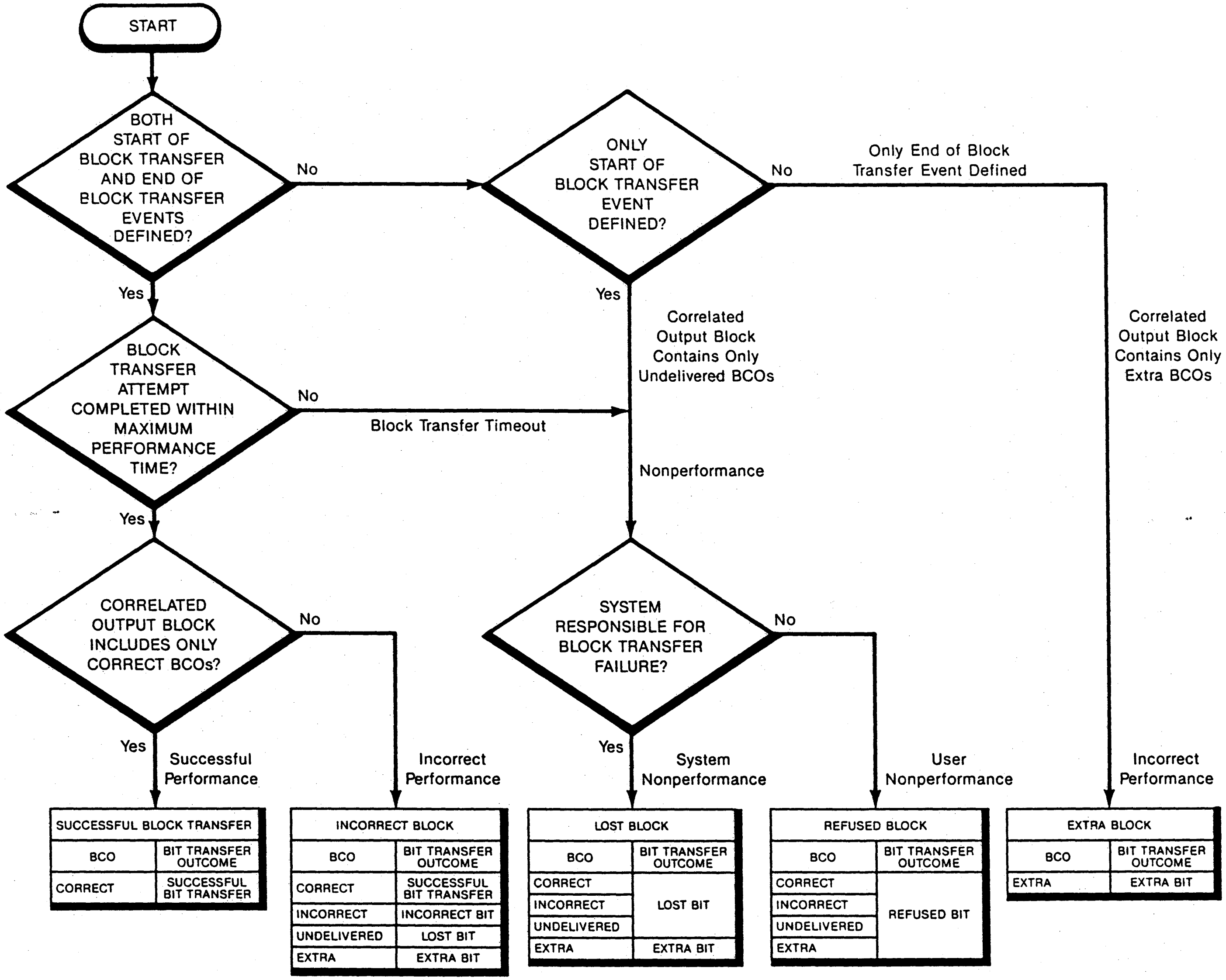


Figure B-7. Scheme for classifying outcomes of bit and block transfer attempts.

associated bits are reclassified as Misdelivered Bits. Misdelivery performance assessment is regarded as an optional process by ANS X3.102 and ANS X3.141.

The third task in user information transfer performance assessment is selecting a sequence of transfer samples for the measurement of Transfer Denial Probability and classifying the outcome of each sample. Guidelines in ANS X3.141 specify that a transfer sample includes an integral number of successive block transfer attempts (in a single data communication session) and the interblock gaps that precede each attempt. Collectively, the block transfer attempts included in a sample should contain a sufficient number of bit transfer attempts to provide the precision specified in ANS X3.102 for estimating each supported failure probability parameter. Guidelines in ANS X3.141 also specify that transfer sample input begins with the start of the interblock gap (at the source user interface) that precedes the first block transfer attempt in the sample. This event normally corresponds to Start of Block Transfer for the last block transfer attempt that precedes the sample. Transfer sample input normally ends with Start of Block Transfer for the last block transfer attempt included in the sample. Transfer sample output begins with the start of the interblock gap (at the destination user interface) that precedes the first block transfer attempt in the sample. This event normally corresponds to End of Block Transfer for the last block transfer attempt that precedes the sample. Transfer sample output normally ends with End of Block Transfer for the last block transfer attempt included in the sample. When a transfer sample has been selected, the assessment procedure classifies its outcome--Successful Transfer, Transfer Denial, or Rejected Sample--according to criteria defined in ANS X3.102. A logical scheme that implements those criteria is shown in Figure B-8. If the measured value of User Information Bit Transfer Rate for the sample is less than the associated threshold value, the assessment procedure assigns responsibility for excessive delay as outlined in Section A.3. User performance time needed in this determination is obtained by using the performance time allocation procedure described later in this section. Rejected Sample outcomes are excluded from the set of trials used to calculate measured values of Transfer Denial Probability.

The fourth task in user information transfer performance assessment is selecting a transfer sample for the measurement of long-term throughput parameters (User Information Bit Transfer Rate and User Fraction of Input/Output Time) and evaluating the associated performance statistics. The

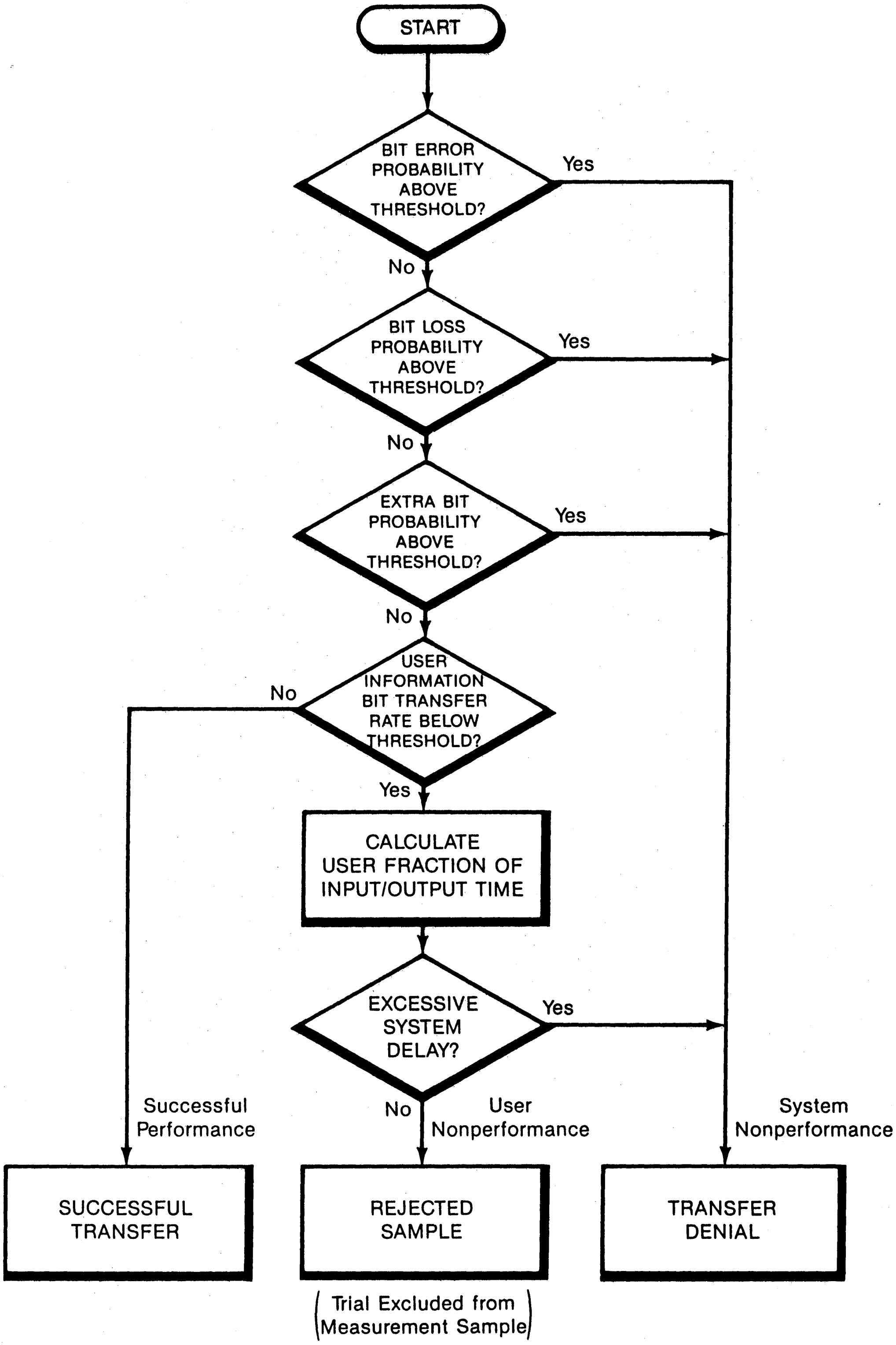


Figure B-8. Scheme for classifying outcomes of transfer samples.

latter includes the number of successfully transferred user information bits in the sample and both overall and user performance times for sample input and sample output. Like its Transfer Denial counterpart, a throughput transfer sample consists of an integral number of successive block transfer attempts (in a single data communication session) and the interblock gaps that precede each attempt. Throughput sample input and output begin and end as described previously for samples used in Transfer Denial measurements. To ensure that performance times for both sample input and output are defined, a throughput sample must be preceded by and end with block transfer attempts for which both Start of Block Transfer and End of Block Transfer are defined. The throughput sample should be selected so that sample input and output times are nearly equal. The larger of the observed user performance times for sample input and sample output is used to estimate User Fraction of Input/Output Time. In the measurement of long-term throughput, note that a performance trial corresponds to a throughput sample.

The fifth (and last) task in user information transfer performance assessment, estimating the ANS X3.102 performance parameters from the observed outcomes, is carried out after all performance trials recorded in the extracted data have been identified and classified.

B.3.4 Disengagement Performance Assessment Procedure

The disengagement performance assessment procedure

- o identifies disengagement attempts recorded in a corresponding pair of reference event histories,
- o classifies the outcome of each identified disengagement attempt, and
- o estimates disengagement performance parameters from the observed outcomes.

This assessment procedure is analogous to that illustrated in Figure B-3 for the access function.

The beginning of each disengagement attempt corresponds to a Disengagement Request (reference event 8 in Table B-1). In a connection-oriented session, the first Disengagement Request is interpreted as the start of disengagement for both users; in a connectionless session, there is a separate Disengagement Request for each user. In either case, the end of a disengagement attempt for a particular user corresponds to a Disengagement Confirmation (reference event 9 in Table B-1) at the local user interface.

When a disengagement attempt has been identified, the assessment procedure uses criteria defined in ANS X3.102 and summarized in Table A-1 of this report to classify and record the outcome: Successful Disengagement, Disengagement Denial, or User Disengagement Blocking. A logical scheme that implements those criteria is presented in Figure B-9. If disengagement timeout occurs, the assessment procedure assigns responsibility for the excessive delay as outlined in Section A.3. User performance time needed in this determination is obtained by using the performance time allocation procedure described later in this section. When there is a significant difference between the disengagement performance of a monitored pair of source and destination users, disengagement attempts for the two users should be segregated in separate samples and used to estimate a separate set of disengagement parameter values for each user. Otherwise, disengagement attempts for the source and destination users may be aggregated in a single sample and used to estimate a set of disengagement parameter values that describe the average performance of both users.

When all disengagement attempts recorded in the extracted performance data have been identified and classified, the assessment procedure estimates the disengagement performance parameters from the observed outcomes.

B.3.5 Performance Time Allocation Procedure

The performance time that is attributable to a user, during a specified performance period, is required to

- estimate values of ancillary performance parameters and
- assign responsibility for timeout failures to either the system or the users.

The user performance time is determined by a performance time allocation procedure as outlined in Figure B-10a. Input to the procedure consists of

- a consolidated ancillary event history specifying local responsibility states at both monitored interfaces,
- information specifying the beginning and end of a particular performance period, and
- information specifying the interface(s) that are relevant in determining overall responsibility during the period.

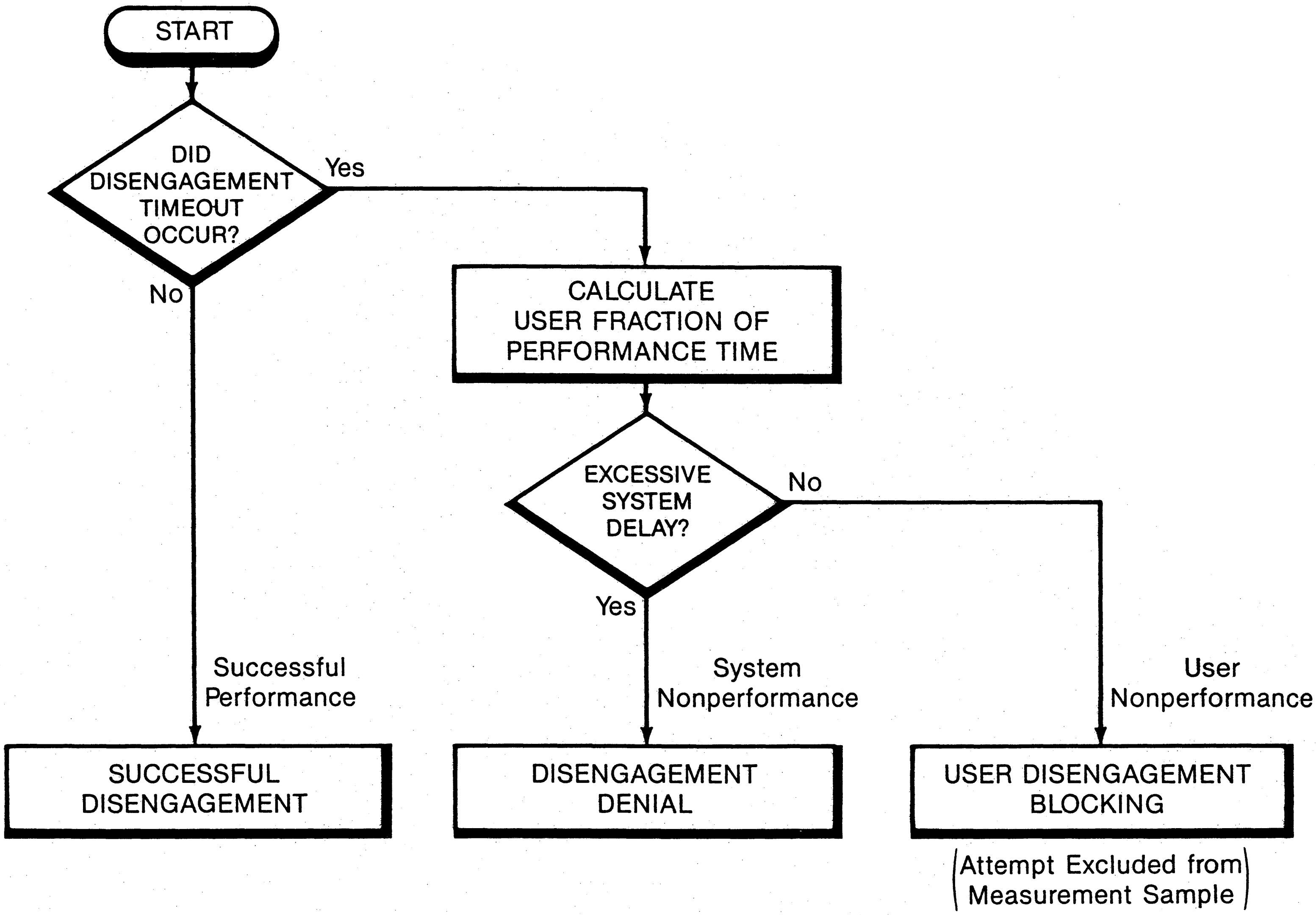
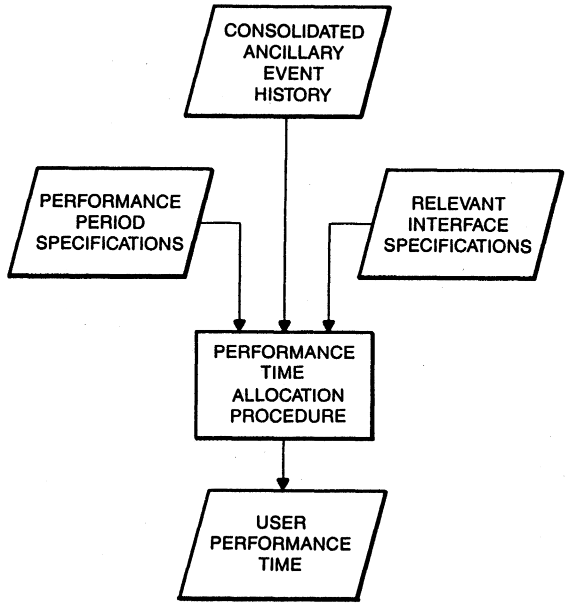
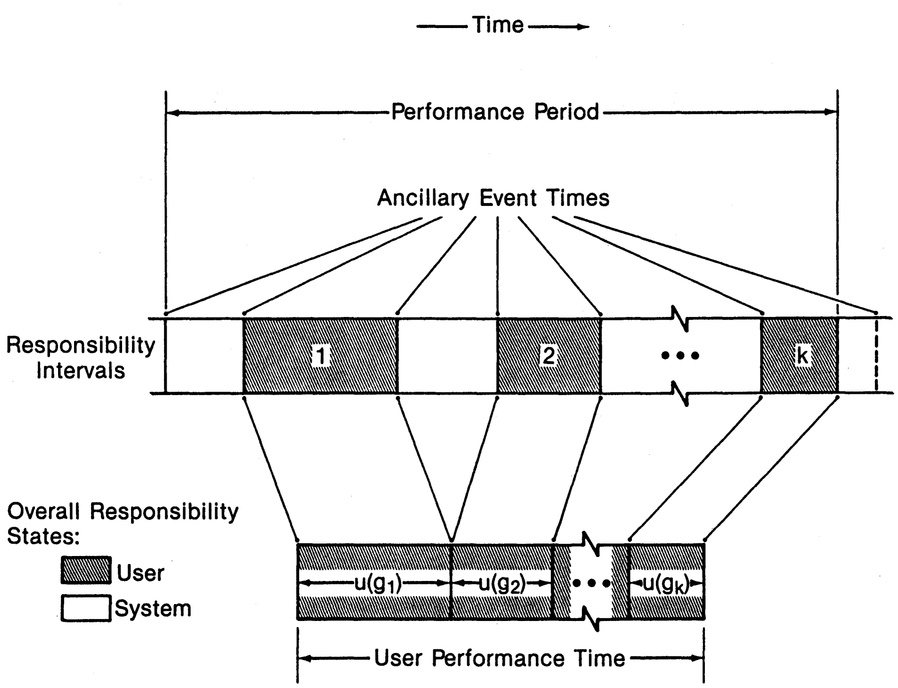


Figure B-9. Scheme for classifying outcomes of disengagement attempts.



a. Outline of the Performance Time Allocation Process



$$u(g) = \sum_{i=1}^{k} u(g_i)$$

b. Performance Time Allocation Concepts

Figure B-10. Summary of performance time allocation.

The performance time allocation procedure examines the consolidated ancillary event history to identify intervals of overall user responsibility within the specified performance period, and determines the user performance time during that period. Basic concepts used in the performance time allocation procedure are illustrated in Figure B-10b. A performance period is divided into a sequence of responsibility intervals by the ancillary events included in the period. Associated with each interval is an overall responsibility state based on the local responsibility state at the interface or interfaces that are relevant for the particular performance period. The user performance time in a performance period is the sum of the durations of the intervals of overall user responsibility within that period.

User performance time may be calculated for any of four types of performance periods. They are

- the period between the beginning and end of an access attempt,
- the period between the beginning and end of a block transfer attempt,
- the period between the beginning and end of transfer sample input or transfer sample output, or
- the period between the beginning and end of a disengagement attempt.

The interface or interfaces that are relevant in evaluating user performance time are specified in Figure B-11a for each type of performance period. A negotiated disengagement attempt requires a concurring response from the user not originating the disengagement request, whereas an independent disengagement attempt does not. If only one monitored interface is relevant in a performance period, the overall responsibility state for a particular responsibility interval is identical to the local responsibility state at the relevant interface (as recorded in the consolidated ancillary event history). If both monitored interfaces are relevant, the overall responsibility state is jointly determined by the two local interface responsibility states according to the scheme presented in Figure B-11b. That scheme includes a pair of split responsibility states in which the user is responsible at one interface and the system is responsible at the other. In the allocation of performance time, intervals of split responsibility are accounted for by including them in the earliest subsequent interval of overall user or system responsibility. If a user and the system simultaneously delay completion of a function,

TYPE OF PERFORMANCE PERIOD	CONDITIONS	RELEVANT INTERFACES
ACCESS ATTEMPT	CONNECTION-ORIENTED	SOURCE AND DESTINATION USER
	CONNECTIONLESS	SOURCE USER ONLY
BLOCK TRANSFER ATTEMPT	ALL	DESTINATION USER ONLY
TRANSFER SAMPLE INPUT OR OUTPUT	RESPONSIBILITY DEFINED AT LOCAL INTERFACE	LOCAL USER ONLY
	RESPONSIBILITY UNDEFINED AT LOCAL INTERFACE	REMOTE USER ONLY
DISENGAGEMENT ATTEMPT	INDEPENDENT	REQUESTING USER ONLY
	NEGOTIATED	SOURCE AND DESTINATION USER

a. Relevant Interfaces

Local Responsibility State at Source Interface

Local Responsibility State at Destination Interface	USER RESPONSIBLE	SYSTEM RESPONSIBLE	RESPONSIBILITY UNDEFINED
USER RESPONSIBLE	USER RESPONSIBLE	"SPLIT" RESPONSIBLITY	USER RESPONSIBLE
SYSTEM RESPONSIBLE	"SPLIT" RESPONSIBILITY	SYSTEM RESPONSIBLE	SYSTEM RESPONSIBLE
RESPONSIBILITY UNDEFINED	USER RESPONSIBLE	SYSTEM RESPONSIBLE	

Overall Responsibility States

b. Overall Responsibility States

Figure B-11. Relevant interfaces and overall responsibility states for performance time allocation.

responsibility for the joint delay is thus attributed to whichever entity delays longer.

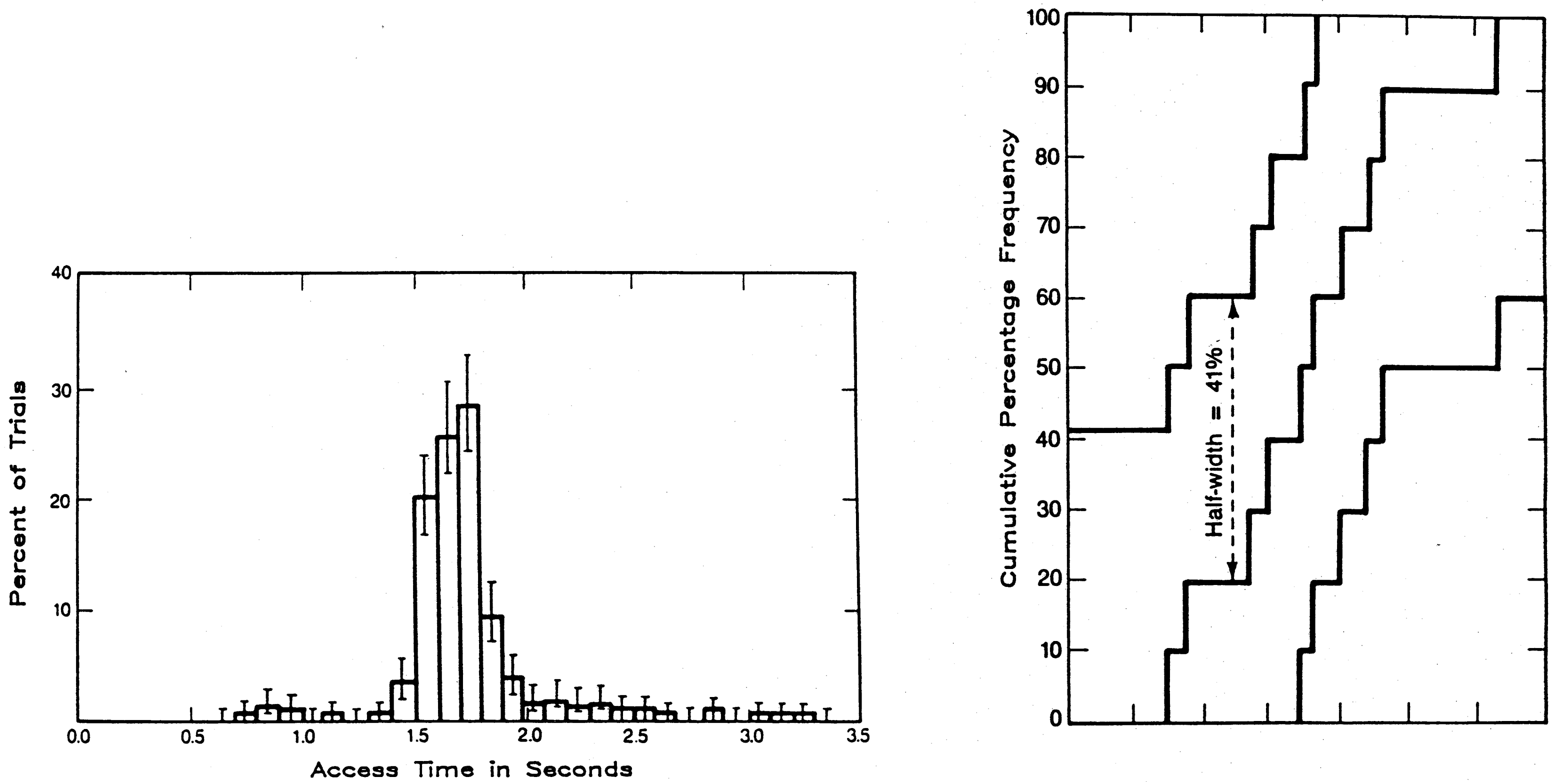
B.4 Data Analysis

In the data analysis phase of the ANS X3.141 measurement process, reduced performance data are examined to estimate parameter values and determine the precision of the estimates. ANS X3.141 outlines methods for analyzing reduced performance data and specifies statistical information that should be included in measurement results for each of the three types of experiments identified in the standard: performance characterization, simple hypothesis testing, and analysis of factor effects.

B.4.1 Performance Characterization

Performance characterization experiments, as described earlier, estimate the performance of data communication service under a single combination of factor levels, without reference to factor effects or to previously specified performance values. Because of sampling error, a parameter estimate cannot be expected to coincide with the population value. The primary task in the data analysis phase of a performance characterization experiment is to estimate the parameter values and the precision of the estimates. This precision is expressed in terms of a confidence interval and an associated confidence level. The standard does not include procedures for determining confidence limits, but refers users to those described by Miles (1984) and implemented in an associated computer program.

To provide additional information about the populations, the reported results may include histograms or cumulative distribution diagrams of observed delays. Because of sampling error, histograms and cumulative distributions differ from the population distribution. The precision with which a (sample) histogram represents the (population) distribution can be described by placing confidence limits above and below the value for each bin, as shown in Figure B-12a. For a prescribed confidence level, the confidence limits associated with each bin may be calculated from the measured values falling within the bin. Note that such confidence limits apply only to each bin, rather than to the entire histogram. In a similar way, the precision with which a (sample) cumulative distribution function represents the (population) distribution function can be described by constructing a "confidence band"



a. Typical Histogram with 95% Confidence Limits

b. Typical Cumulative Distribution Diagram with 95% Confidence Band

Figure B-12. Typical histogram and cumulative distribution diagram with associated confidence limits.

about the sample function as illustrated in Figure B-12b. The upper confidence band is obtained by adding a constant value, determined from the sample and the prescribed confidence level, to each value of the sample distribution function. The lower confidence band is obtained by subtracting the same value from each distribution function value. Details of the procedure are described by Crow et al. (1960).

B.4.2 Simple Hypothesis Testing

In the simple hypothesis test, a performance parameter is estimated under a single combination of factor levels and compared with a specified value in order to decide whether to accept or reject a given hypothesis about the relationship between the estimated and true parameter values. Two common examples of hypotheses are the following:

- o Performance (represented by a true population parameter value) is equal to a specified value.
- o Performance is equal to or better than a specified value.

Because a parameter estimate based on a sample may differ substantially from the population parameter value, decisions concerning tested hypotheses are normally made with some uncertainty. This uncertainty is expressed by the significance level (α) of the experiment: the probability of rejecting the tested hypothesis when it is true (i.e., the probability of a type I error). The principal task in the data analysis phase of a simple hypothesis test experiment is to determine, on the basis of the data and the prescribed significance level, whether to accept or reject the tested hypothesis.

Given a significance level, α, the first hypothesis (above) can be examined by the following procedure:

- o Estimate the confidence interval that corresponds to the $(1-\alpha)$ X 100% confidence level.
- o Compare the specified parameter value with the estimated confidence interval. If the confidence interval contains the specified value, the hypothesis is accepted (with a probability of error no greater than α). If the hypothetical value lies outside the confidence interval, the hypothesis is rejected.

The above procedure can be applied to the second hypothesis (above) by calculating the confidence interval that corresponds to the $(1-2\alpha)$ X 100% confidence level. The hypothesis is accepted if the interval contains the specified parameter value or lies on the "high performance" side of that value, and is rejected otherwise. The complements of the preceding hypotheses (i.e., performance differs from a specified value and performance is worse than a specified value, respectively) can be examined by an approach similar to that just outlined.

In some hypothesis test experiments, it may be necessary to consider the probability of accepting the stated hypothesis when it is actually false (i.e., the probability of a type II error). The probability of such an error depends on the prescribed significance level of the experiment, the sample size, and the difference between the specified and true (population) parameter values. For a description of the analysis of type II errors, ANS X3.141 refers users to Crow et al. (op. cit.). An example is included in Appendix B of the standard.

B.4.3 Analysis of Factor Effects

In experiments designed to analyze factor effects, tests are conducted under several factor level combinations. ANS X3.141 recommends that analysis of variance be used to evaluate the effects of factors on time and rate parameters and that an equivalent analysis of the chi-squared statistic be used in the case of failure probabilities. In both cases, the measurement standard refers the user to existing publications (Crow et al., 1960; Miles, 1984) for detailed descriptions of the relevant procedures.

If factor levels are quantifiable, regression analysis may be employed with a suitably chosen mathematical function to represent the relationship between parameter values and factor levels. If parameter values are represented by a function of a single factor, regression on that factor (e.g., linear or polynomial) is used to fit the assumed function to the data. Multiple regression is used in cases where parameter values are represented by a function of two or more factors. Linear functions are often employed in both simple and multiple regression analyses to represent the dependence of parameter values on factor levels. An example of a linear relation, illustrated in Section 5.3.1 of this report, is Block Transfer Time as a function of block size. An assumed regression function, whether linear or nonlinear, is usually fitted to the measured parameter values by the method of least squares, as described (for example) by Dixon and Massey (1969). A regression function derived from sample data usually differs from the true population regression function because of sampling error. The precision of a sample regression function can be described quantitatively as follows:

- Calculate the standard deviation about the regression function (which represents the parameter variability that is not accounted for by the regression function).
- Calculate confidence limits for representative values of the sample regression function.
- Test calculated sample regression coefficients for significant differences from zero.

Procedures for these calculations are given by Crow et al. (op. cit.).

Relationships between pairs of random performance variables (e.g., delay and throughput) may be examined by a correlation analysis. In a typical correlation analysis, observed pairs are plotted as a scatter diagram and the sample correlation coefficient is calculated. In addition, it is often useful to fit a selected function (e.g., a straight line) to the data by the methods of regression analysis. The precision with which a regression curve, fitted to sample data, approximates the population regression curve can be described by the three measures outlined previously. As an alternative to testing the significance of the sample regression coefficient, a significance test of the sample correlation coefficient may be conducted to decide if it differs significantly from zero.

Very often, if not usually, analysis of factor effects is necessary to realistically characterize the performance of a data communication service. This is discussed briefly in Section 2.2.4 and in detail in Appendix H of the present report.

B.5 References

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APPENDIX C: SUMMARY OF SWITCHED NETWORKS

The tests reported here were conducted over three public data networks (Telenet, Tymnet, and Uninet), the public switched telephone network (PSTN), and the Federal Telecommunications System (FTS). The attributes of these five networks are summarized in this appendix with emphasis on the fundamental architectural differences between them. The features described are those that existed in 1983 when the tests were conducted. Both the architecture and operation of some of these networks may have undergone changes since that time.

The basic concepts of packet switching are described in a text by Rosner (1982). These concepts are generally applicable to all of the public data networks (PDNs) used in the ITS tests; the reference includes descriptions of flow control, error control, and network protocols.

C.1 Telenet

A simplified view of the Telenet configuration is illustrated in Figure C-1. The network's nodes, called Telenet Central Offices (TCOs), were connected in a three-level hierarchy. Intra-network protocol was based on CCITT Recommendation X.75 for connecting public data networks (CCITT, 1985b). Class 1 TCOs were connected through at least three paths, and each Class 2 and Class 3 TCO was connected to a Class 1 TCO. Each TCO was similar to the Interface Message Processor (IMP) used in the ARPANET. Messages from host processors or terminals were reorganized into packets either by a TCO or by subscriber equipment and sent into the network. Packets were then forwarded according to a routing table stored in the TCO.

Telenet packets contained up to 128 characters and were dedicated to one user. The average packet included 20 to 40 characters. Telenet charges were based on the number of packets transferred, regardless of the distance.

The Telenet switches, known as Telenet Processor 4000 Packet Switches, were modular so that the processing capability could be increased incrementally at any node. Each switch contained a master central processing unit (CPU) and a number of slaves called line processing units (LPUs). The CPU and LPUs communicated via a common memory.

Route selection in Telenet was a two-step process at each node. The two steps were a routing table search, followed by link selection. The routing table search selected a set of feasible outgoing links based on the destination address. A specific link was then selected by an algorithm that took into

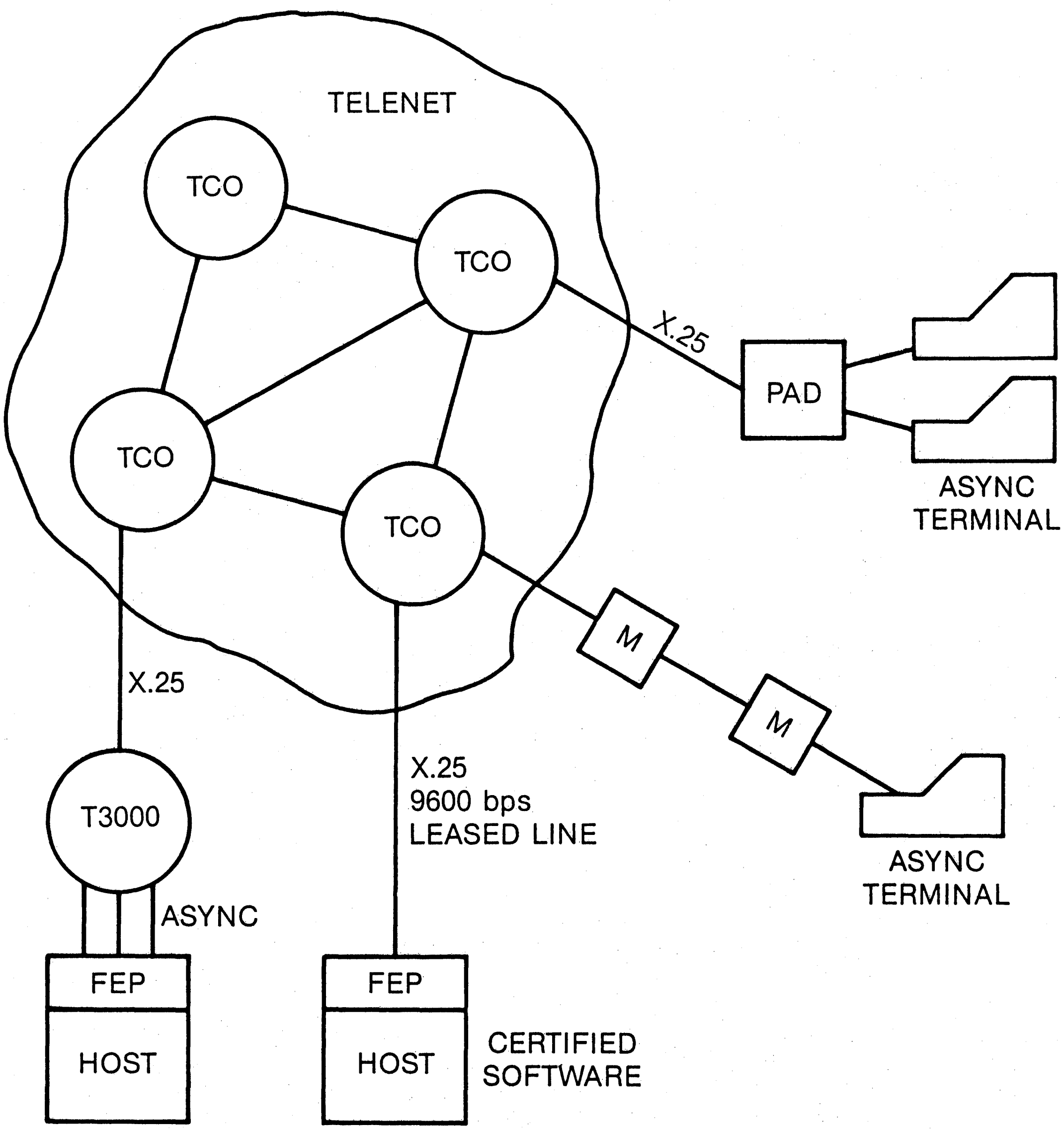


Figure C-1. Telenet configuration.

account several factors such as topology, link capacity, utilization, and estimated throughput. The route selected at call set-up was then used for all packets in the call.

Telenet provided service for terminals operating from 110 bps to 56,000 bps. A virtual circuit was selected as the path of least delay on a call-by-call basis. An error control code checked each packet for transmission errors. Packets containing errors were retransmitted at no cost to the customer. Asynchronous terminals could communicate with incompatible terminals of lower speed as long as the network was not required to store more than 500 characters. Terminal connections to TCOs could be public or private dial-up ports or dedicated ports. Both hardware and software interfaces to the network were available using CCITT X.25 protocol (CCITT, 1985a).

Costs were based on the connection time (measured from initiation to termination of the connection) and the amount of data transferred (measured in kilopackets, regardless of their size).

C.2 Tymnet

The configuration of Tymnet, a centrally directed public packet switched network, is summarized in Figure C-2. Network switching nodes, connected by voice-grade lines, would store and forward data packets from node to node. Each packet contained up to 66 bytes or characters from as many as 20 calls. Unlike Telenet, Tymnet packets could be repackaged at each node for the next hop. Routing was not distributed but each call was routed by a central supervisor as shown in Figure C-2. During call set-up, a virtual circuit was established by one node which acted as the supervisor. This supervisor controlled the network and managed all network resources including topology, failures, and current traffic conditions. It established the optimum path in terms of minimum delay and local conditions. The supervisor also collected accounting and network status information.

Tymnet controlled the average input-output rate to a node by examining storage buffers associated with each input process. When a specified threshold in these buffers was reached, the input process was signaled to stop accepting data until further notice.

Tymnet provided access with protocol and speed conversion capabilities similar to those of Telenet and Uninet. The network could be accessed through

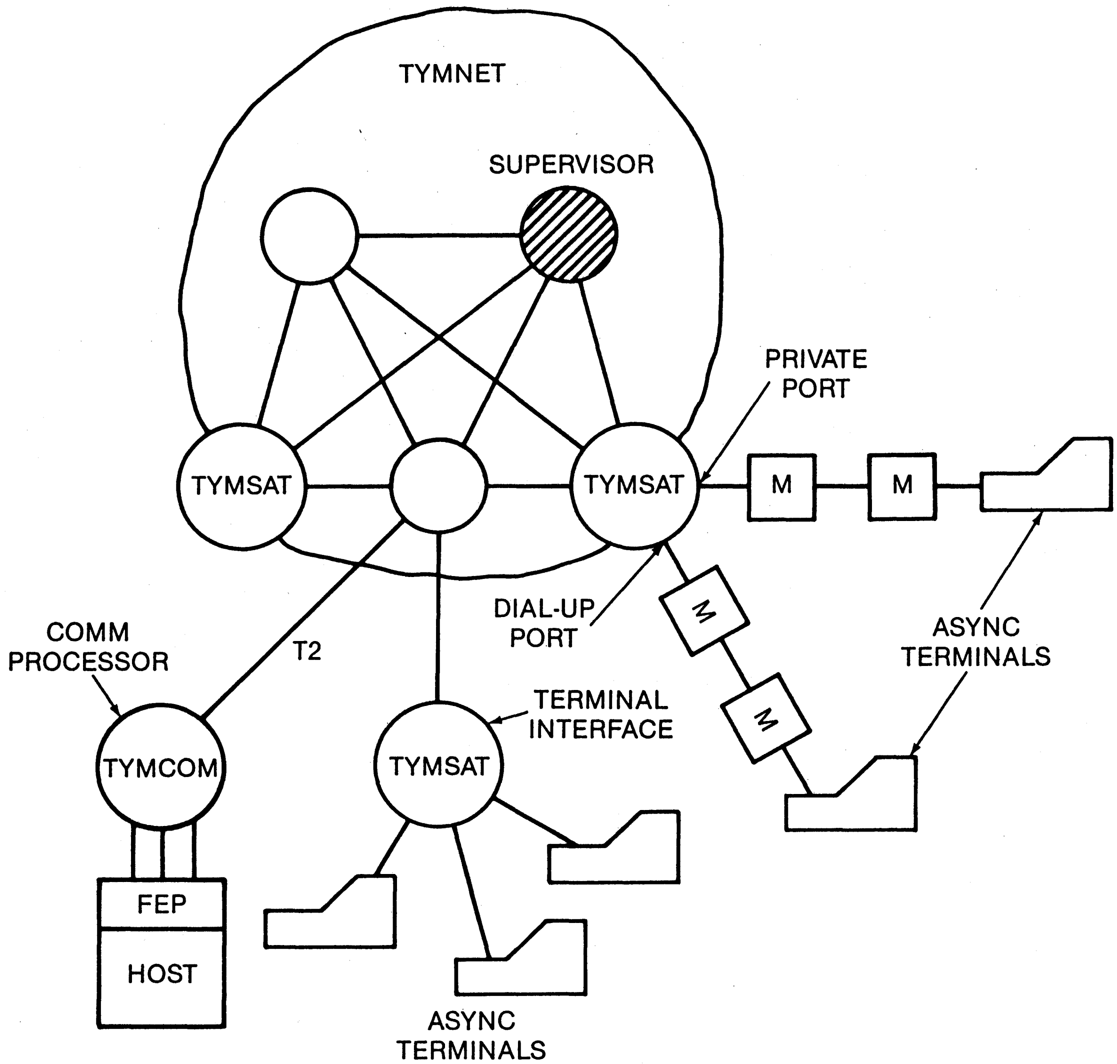


Figure C-2. Tymnet configuration.

public or private dial-up ports or through dedicated ports. Transmission speeds ranged up to 2400 bps using conventional modems.

The nodes were interfaced and controlled by a specially designed system of protocols known as the Internally Switched Interface System (ISIS). Nodes were connected by either leased lines or microwave and satellite circuits. Transmission speeds ranged from 4800 bps to 56,000 bps. Terminal interfaces, known as Tymsats, provided access to user terminals with a variety of synchronous and asynchronous protocols, including CCITT X.25. Host interfaces, known as Tymcoms, also provided synchronous or asynchronous connections to Tymnet nodes.

Costs depended on connection times to the network and on the number of characters transmitted. Tymnet charged by the kilocharacter, rather than by the kilopacket as did Telenet, because users could share packets. This shared-packet technique resulted in a shorter transmission delay.

C.3 Uninet

As shown in Figure C-3, Uninet was a four-level network structure consisting of Interregional and Intraregional switching nodes, interconnect nodes (ICNs), and PADs. The switching nodes were connected with 56,000 bps dedicated transmission links. Substantial redundancy was included for reliability. The ICNs provided network interfaces from the user hosts or PADs through an X.25 interface. Traffic from the ICN to the Switching Nodes was synchronous and used high-level data link control (HDLC) protocols. Customer terminals and modems were connected using either asynchronous or synchronous interfaces. Host connections were asynchronous, X.25, SDLC/SNA, or bisynchronous.

Customers selected public or private dial-up ports or dedicated ports. Access was through terminal packet assembler/disassemblers (TPADs). The network supported asynchronous interactive service at transmission speeds from 110 bps to 1200 bps for multiple terminals. Terminal access via modems and dial-up ports was also available to a PAD in the network.

Terminal connection charges were based on the type of access port in terms of traffic density (i.e., high, medium, or low) and the number of kilocharacters transferred.

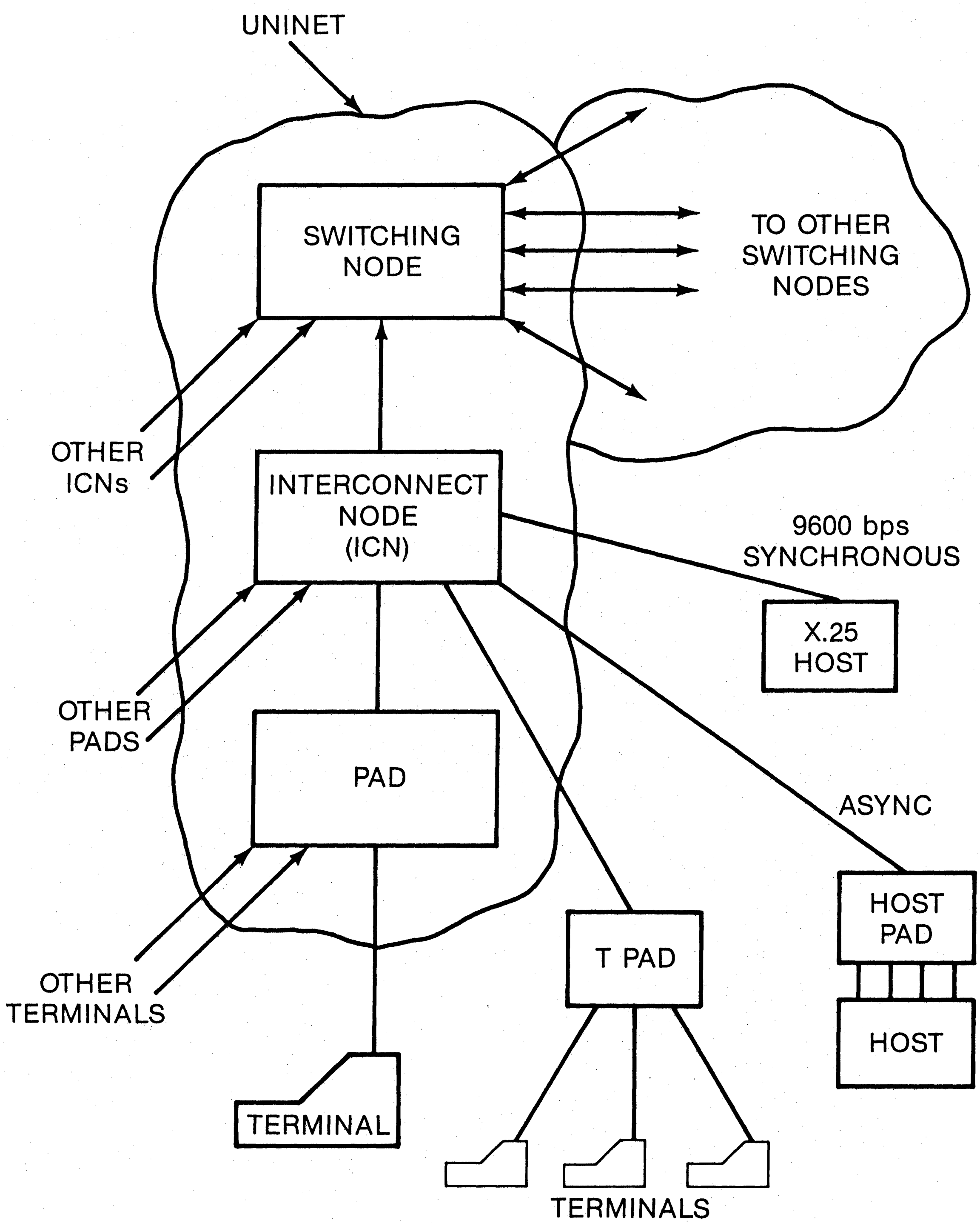


Figure C-3. Uninet configuration.

C.4 Public Switched Telephone Network

In 1983, the Public Switched Telephone Network in the United States included AT&T, the 22 Bell Operating Companies, and approximately 1500 independent telephone companies. The number of subscribers in the United States was nearly 200 million, 80% of which were served by the Bell System.

The transmission facilities that made up this vast network ranged from analog local loops to trunks. The traffic on the long distance trunks was largely carried by co-axial cable, microwave, and satellite transmission facilities. Switches ranged from small (fewer than 100 lines) to large (more than 100,000 lines) and from old (mechanically controlled analog switches) to modern (computer-controlled digital switches)--all in the same network. In 1983, large portions of the network were in the process of being converted to digital transmission and switching, but many sections still remained analog. The signaling that remotely controlled these switches was also in the process of being converted to common-channel interoffice signaling (CCIS) systems that replaced the in-band signaling systems. The CCIS was expected to decrease access and disengagement times by almost one order of magnitude and permit many new services to be offered.

In 1983, the PSTN consisted of a network hierarchy of five levels as depicted in Figure C-4. At the lowest level were the Class 5 switching offices, called end offices (local exchanges). There were approximately 20,000 end offices in the U.S. The next level, Class 4, contained over 1300 toll offices. There were three more levels in this toll network--called primary, sectional, and regional centers. At that time (1983), there were 10 Class 1 regional centers in the United States. Traffic was routed through the lowest available level of the network, since the shorter paths and fewer switching points provided better quality. During periods of heavy traffic, alternate routes were assigned by each switch. Thus, many of the performance parameters for data communication over the PSTN could vary considerably, depending on traffic. Normally the busy hour occurred just before and just after the lunch hour on weekdays.

Unlike the PDNs, which leased digital facilities for transmission from the common carriers, the PSTN consisted of both analog and digital facilities. An analog voice channel was nominally 4 kHz wide. Data modems were designed to operate over this 4 kHz channel using data rates from 300 bps to 9600 bps, depending on the number of information bits/Hz in the modulation scheme. A

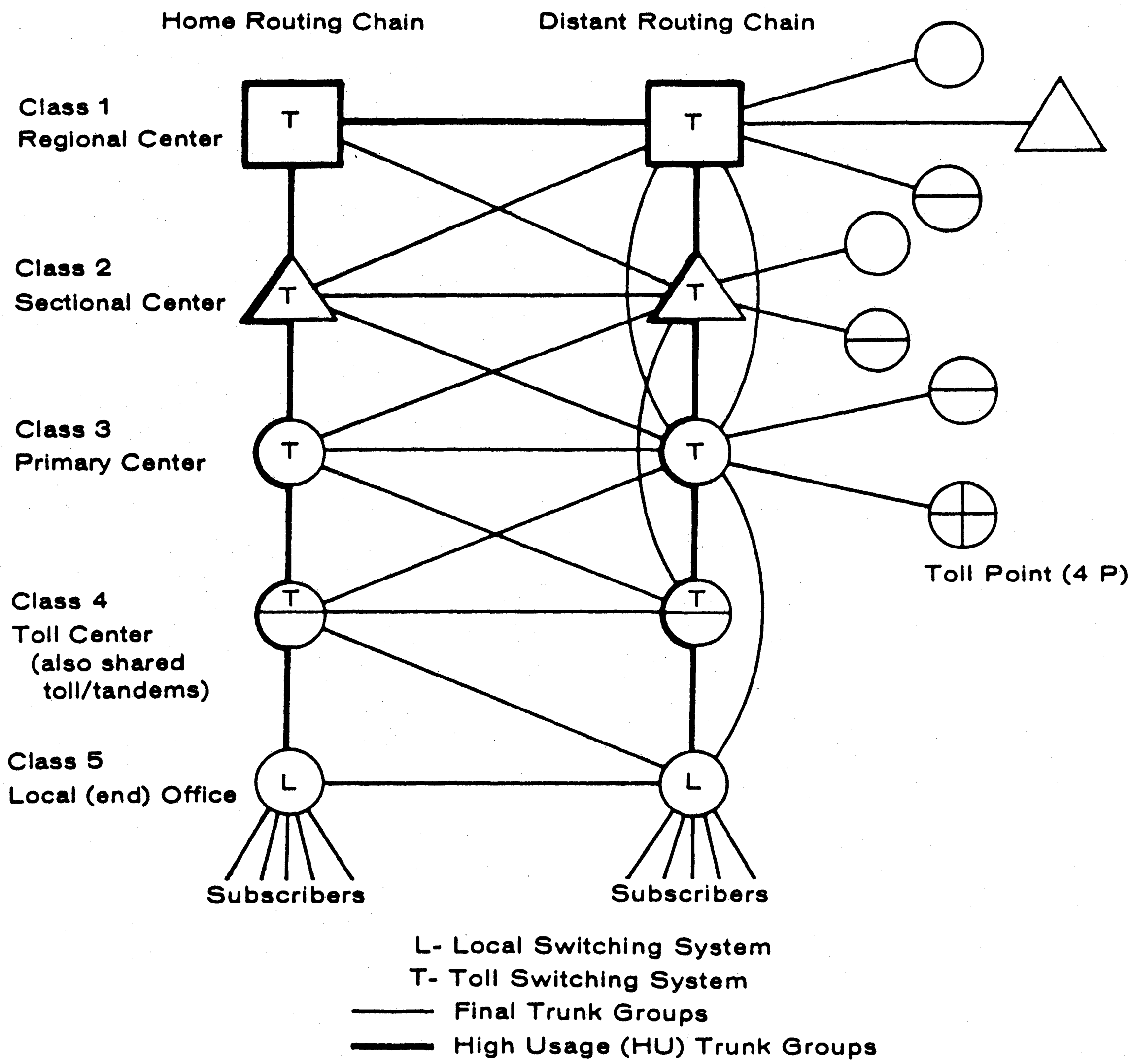


Figure C-4. Network hierarchy and switching plan (after AT&T, 1980).

typical PSTN circuit would include this 4 kHz channel in the local analog loop that connected a user's terminal to the nearest telephone exchange. The circuit connected this local exchange to a Class 4 toll office via a digital trunk. These digital trunks, designated as T-carriers, varied in size. The minimum size operated at 1.544 Mbps. This 1.544 Mbps transmission facility carried 24 voice channels, each digitized at 64,000 bps. Several T-carriers were multiplexed at the toll switch for subsequent transmission over terrestrial cable, microwave radio, or even satellite circuits.

C.5 Federal Telecommunications System

The Federal Telecommunications System (FTS) was the largest private network in the United States in 1983. It provided agencies in the Federal Government with a wide range of services at costs generally below the usual commercial rates. The FTS provided circuit switched services for voice, record, and data traffic. The FTS trunks were usually leased from a common carrier. Switches were either owned or leased as a common-channel switching arrangement (CCSA) whereby portions of the switches are shared with other private networks. Routing through these switches involved a three-level hierarchy as shown in Figure C-5. User PBX installations were generally routed via Class 5 offices of the PSTN to the lowest level FTS switch or by leased trunks with no PSTN switching.

C.6 References

AT&T (1980), Notes on the Network (American Telephone and Telegraph Co., New York, NY).

CCITT (1985a), Red Book Vol. III.3, Data communication networks: interfaces, Recommendations X.20-X.32, pp. 108-242, (ITU, Geneva).

CCITT (1985b), Red Book, Vol. VIII.4, Data communication networks: transmission, signalling and switching, network aspects, maintenance, and administrative arrangements, Recommendations X.40-X.181, pp. 152-236, (ITU, Geneva)

Rosner, R. D. (1982), Packet Switching (Lifetime Learning Publications, Belmont, CA).

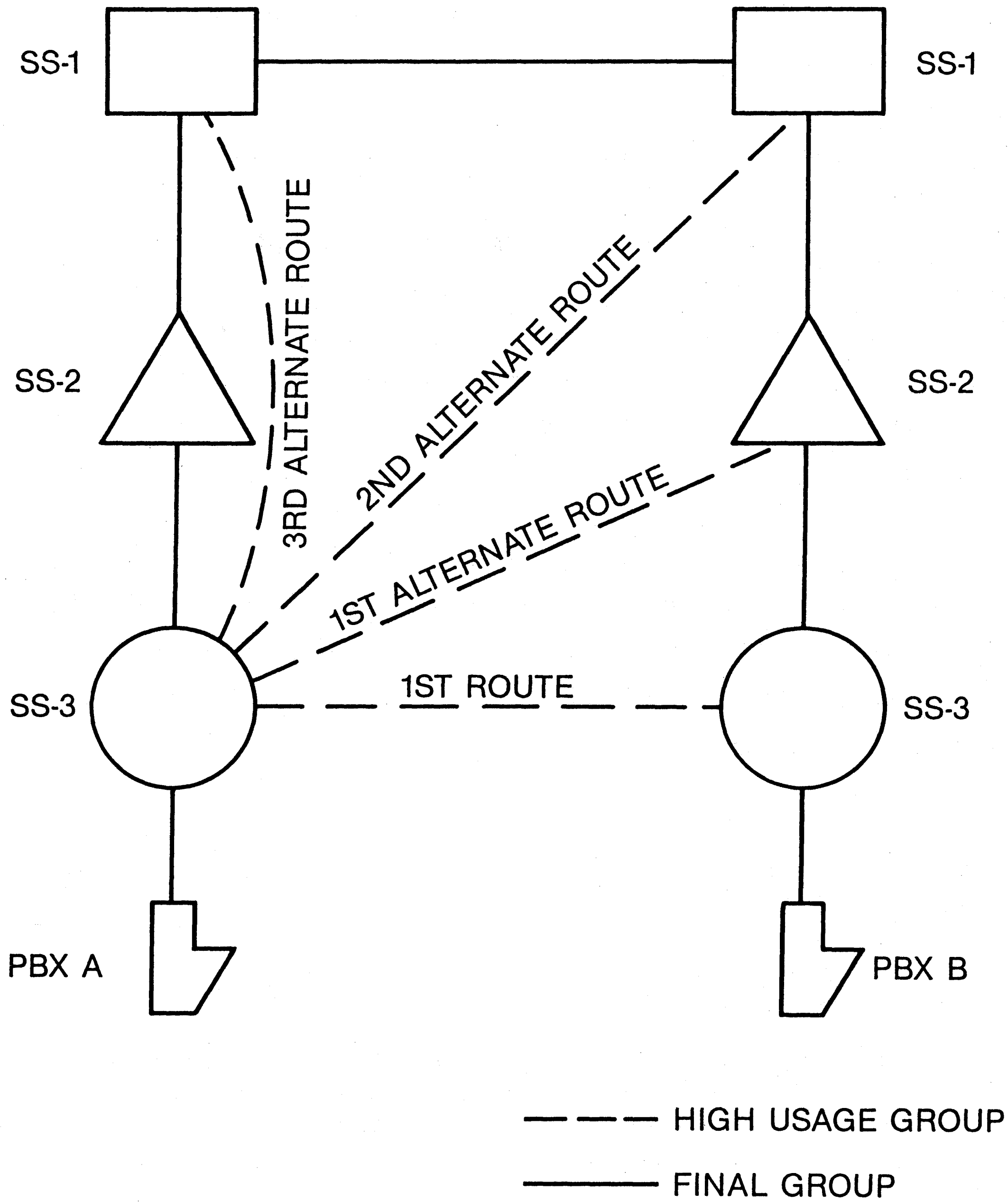


Figure C-5. FTS hierarchy routing.

APPENDIX D: COMMUNICATION STATE MODEL

In the ITS measurements, the representation of reference events recorded in the overhead information files was based on a particular state model of the data communication process. This model is an adaptation of an earlier version defined in Interim Federal Standard 1033 (GSA, 1979), and discussed in detail in a related report (Seitz and McManamon, 1978).

As illustrated in Figure D-1a, the communication state model used here includes four participating (or communicating) entities: a source and destination pair of end users receiving service, and a source and destination pair of conceptual half-systems providing service. Each half-system represents that portion of the end-to-end data communication system that interacts with the adjacent user. This division of the data communication system into two separate entities reflects the fact that system activities underway at one user interface may be completely uncorrelated with those occurring at the other interface during a portion of a data communication session. Each model entity is represented by a simple finite-state machine characterized, at any given time, by a specific communication state which describes the involvement of that entity in a particular data communication session. Primary overhead and ancillary reference events associated with the session are then represented by discrete changes in the communication state of one or more model entities.

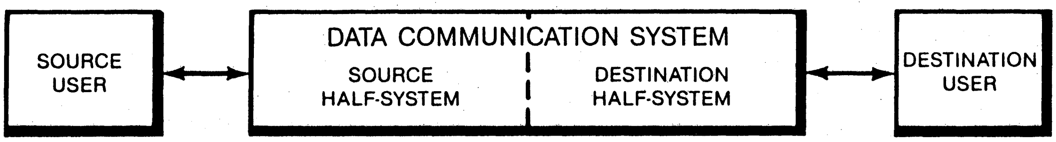
Relative to a given data communication session, each model entity is in one of three primary communication states at any time:

1. Idle State. The entity is not involved in the given session. (The entity can be involved in another session, or can be uninvolved in any session.)

2. Committed State. The entity is involved in the given session, with the intent to transfer (transmit or receive) additional user information.

3. Closing State. The entity is involved in the given session, with the intent to terminate involvement without transferring additional user information.

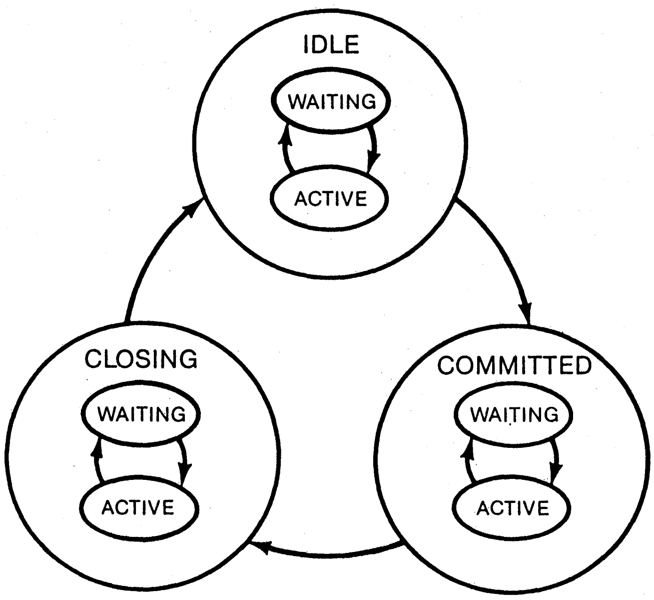
Each of these primary states includes two ancillary communication states: the Active state and the Waiting state. These have different meanings that depend on the associated primary state. Within the Committed and Closing states, the two ancillary states describe an entity's responsibility for producing the next event (associated with the given session) at the local user/system interface. If a given entity is responsible for producing the next



a. Model Entities

COMPOSITE COMMUNICATION STATE (PRIMARY/ANCILLARY)	COMMUNICATION STATE VARIABLES			COMMUNICATION STATE CODE
	CLOSING	COMMITTED	ANCILLARY	
IDLE/WAITING	0	0	0	0
IDLE/ACTIVE	0	0	1	1
COMMITTED/WAITING	0	1	0	2
COMMITTED/ACTIVE	0	1	1	3
CLOSING/WAITING	1	0	0	4
CLOSING/ACTIVE	1	0	1	5

b. Representation of Communication States



c. Communication State Diagram

Figure D-1. Summary of communication state model.

event, that entity is in the Active state; otherwise, the entity is in the Waiting state.

Within the Idle state, the two ancillary states describe an entity's status relative to designated or scheduled service time intervals during which that entity may participate in data communication activities. When an entity is within a service time interval, but is not involved in the given session, that entity is in the Active state. When an entity is not within a service time interval, it is in the Waiting state. A transition between these two ancillary states corresponds to the beginning or end of a service time interval. Note that it is possible for two Idle half-systems within the same data communication system to be in different ancillary states; an example is a worldwide message-switching system that provides service to subscribers only during local business hours.

Together, the three primary and the two ancillary states result in a total of six possible composite communication states. For a given model entity, each composite state is uniquely represented by a sequence of three binary-valued communication state variables, as illustrated in Figure D-1b:

1. Closing State Variable. This describes an entity with respect to the Closing state. It has the value 1 if the entity is in the Closing state and the value 0 otherwise.

2. Committed State Variable. This describes an entity with respect to the Committed state. It has the value 1 if the entity is in the Committed state and the value 0 otherwise.

3. Ancillary State Variable. This variable describes an entity's ancillary communication state. It has the value 1 if the entity is the Active state and the value 0 if the entity is in the Waiting state.

Because an entity is in the Idle state if (and only if) it is not in the Closing state and not in the Committed state, there is no need for a separate state variable to describe an entity with respect to the Idle state. An entity in the Idle state is characterized by the fact that its Closing and Committed state variables both have the value 0.

For convenience in recording and processing performance data, each composite communication state is also represented by a single integer-valued communication state code. This is obtained from the associated communication state variables by regarding them as the binary digits (in the order shown in Figure D-1b) of an equivalent decimal integer.

In the communication state model just described, each primary overhead reference event is represented by a particular primary communication state transition by one or more model entities. Relationships between reference events and the corresponding model events (i.e., communication state transitions) are specified in the following paragraphs:

Access Request. An Access Request corresponds to transitions from the Idle/Active state to the Committed state by the originating user and the adjacent half-system.

Nonoriginating User Commitment. This event corresponds to transitions from the Idle/Active to the Committed state by the nonoriginating user and (when it has not already made that transition) by the adjacent half-system.

System Blocking Signal. This event corresponds to transitions from the Committed state to the Closing state by the originating user and the adjacent (issuing) half-system. The same transitions are associated with a User Blocking Signal and a Disengagement Request. To distinguish it from other reference events, a System Blocking Signal is represented in a communication state history by two successive events having a common event time. In the first, the issuing half-system enters the Closing state, and in the second, the adjacent (originating) user enters the Closing state.

User Blocking Signal. This reference event corresponds to transitions from the Committed state to the Closing state by the issuing user and the adjacent half-system. As indicated above, these transitions are also associated with a System Blocking Signal and a Disengagement Request. To differentiate it from these other events, a User Blocking Signal (like its system counterpart) is represented in a communication state history by two successive events having a common event time. In the first event, the issuing user enters the Closing state, and in the second, the adjacent half-system enters the Closing state.

Disengagement Request. This event corresponds to transitions from the Committed state to the Closing state by the disengaging user and the adjacent half-system. To distinguish it from User or System Blocking Signals (which correspond to the same transitions, as described above), a Disengagement Request is represented in a communication state history by a single event (the identity of the participant issuing a disengagement request is not relevant to performance evaluation).

Disengagement Confirmation. This event corresponds to transitions from the Closing state to the Idle state by the disengaging user and the adjacent half-system.

Ancillary reference events are represented in the communication state model by the appropriate transitions in the ancillary states of the affected entities. When a given interface event corresponds to a primary overhead reference event and to an ancillary event, both reference events are represented by a single model event (except as described previously for User and System Blocking Signals).

References

GSA (1979), Interim Federal Standard 1033, Telecommunications: digital communication performance measurement parameters, August 29 (Published version available from the Office of the Manager, National Communications System Technology and Standards, Washington, DC 20305).

Seitz, N. B., and P. M. McManamon (1978), Digital communication performance parameters for proposed Federal Standard 1033, NTIA Report 78-4, May.

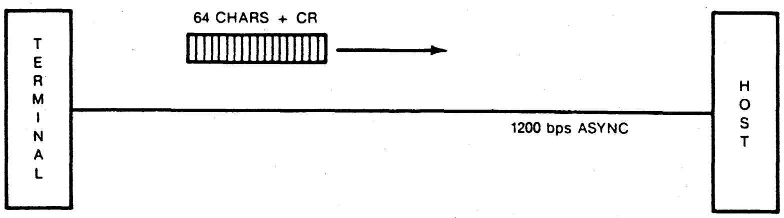
APPENDIX E: TEST EQUIPMENT VALIDATION

An essential part of the measurement program was the calibration of equipment used to perform on-line data extraction. The three configurations shown in Figure E-1 were used in conducting a series of block transfer time bench tests in the laboratory. For comparison, Figure E-2 shows the configuration used for actual tests of PDN connections, along with some typical test results.

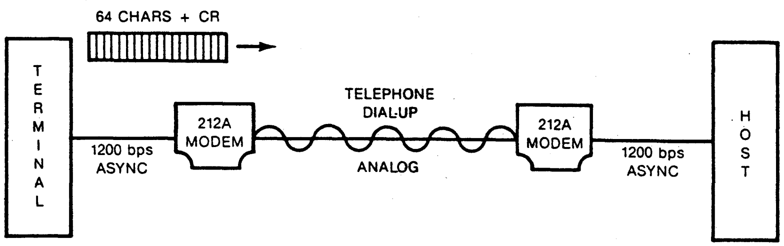
The first configuration tested in the laboratory was a direct RS 232 C connection (with a null modem crossover) operating at 1200 bps between the two test computers (Figure E-1a). Chronological plots of block transfer times for 64-character blocks using this configuration are shown in Figure E-3. Figure E-3a shows results for a test in which there was an extra 1-second pause between the input of successive blocks (low utilization), and Figure E-3b shows results for a test in which there was no extra pause between the input of successive blocks (high utilization). As discussed in Section 5.3.1, the sawtooth pattern of block transfer times was the joint result of the block size, the size of a UNIX™ buffer associated with the communication port of the computer, and the manner in which the operating system transferred characters from the DATA.X file into that buffer. Note that the minima in the sawtooth pattern are nearly equal to the almost constant value of block transfer times observed in the low-utilization test. The difference of only 8 milliseconds between the calculated transmission time and the measured block transfer time for low utilization (see Figure E-1a) demonstrates the accuracy of the measurement system.

The second laboratory configuration tested required dialing the local commercial telephone exchange and sending blocks over a 1200 bps modem (Figure E-1b). Chronological plots of block transfer times for a low-utilization test and a high-utilization test using this configuration are shown in Figure E-4. The difference between the computed transmission time and the measured block transfer time for low utilization (see Figure E-1b) is greater in this case. The larger difference is probably due to the additional single-character buffering in each modem.

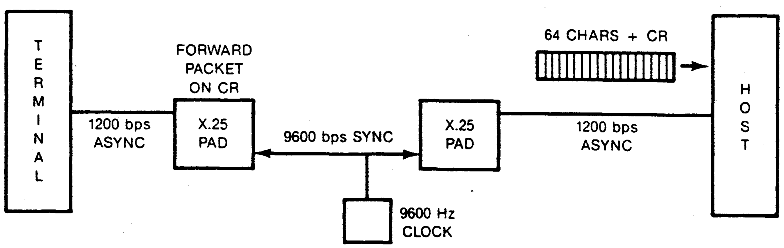
The last laboratory configuration tested used a pair of X.25 PADs to connect the two computers (Figure E-1c). A chronological plot of block transfer times for a high-utilization test using this configuration is shown in Figure E-5.



a. Hardwired Back-to-Back Connection



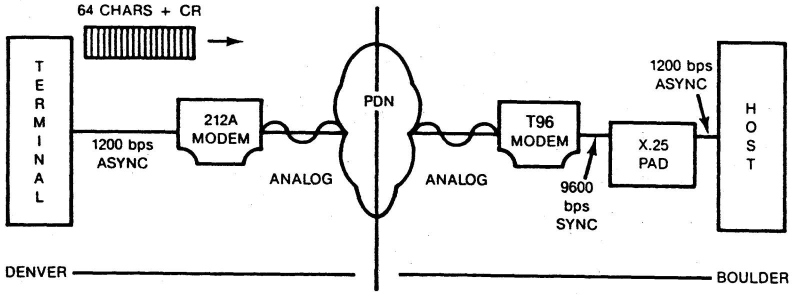
b. Connection via Local Dial-up Exchange



c. Hardwired X.25 Connection

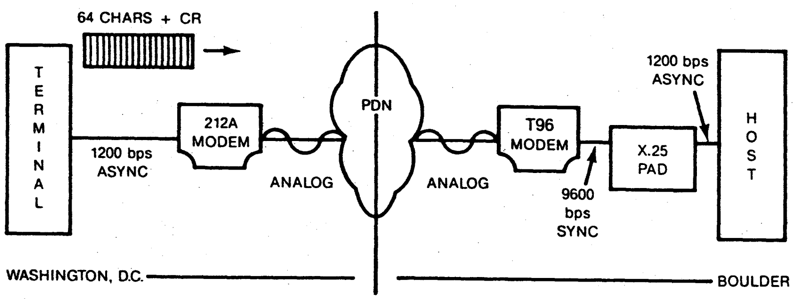
TEST NUMBER	TRANSMISSION TIME (milliseconds)	MEASURED TRANSFER TIME (milliseconds)	DIFFERENCE (milliseconds)	COMMENTS
1098	542	550	8	Measurement System Accuracy
1100	542			
1097	542	572	30	Modem and Circuit Delays
1084	542			
1094	1152			PAD Delays and Overhead

Figure E-1. Bench calibration of test equipment.



TEST NUMBER	TRANSMISSION TIME WITHOUT PDN (milliseconds)	MEASURED TRANSFER TIME (milliseconds)	PDN DELAY (milliseconds)	COMMENTS
436	1198	1363	165	PDN A
675	1198	1380	182	PDN B

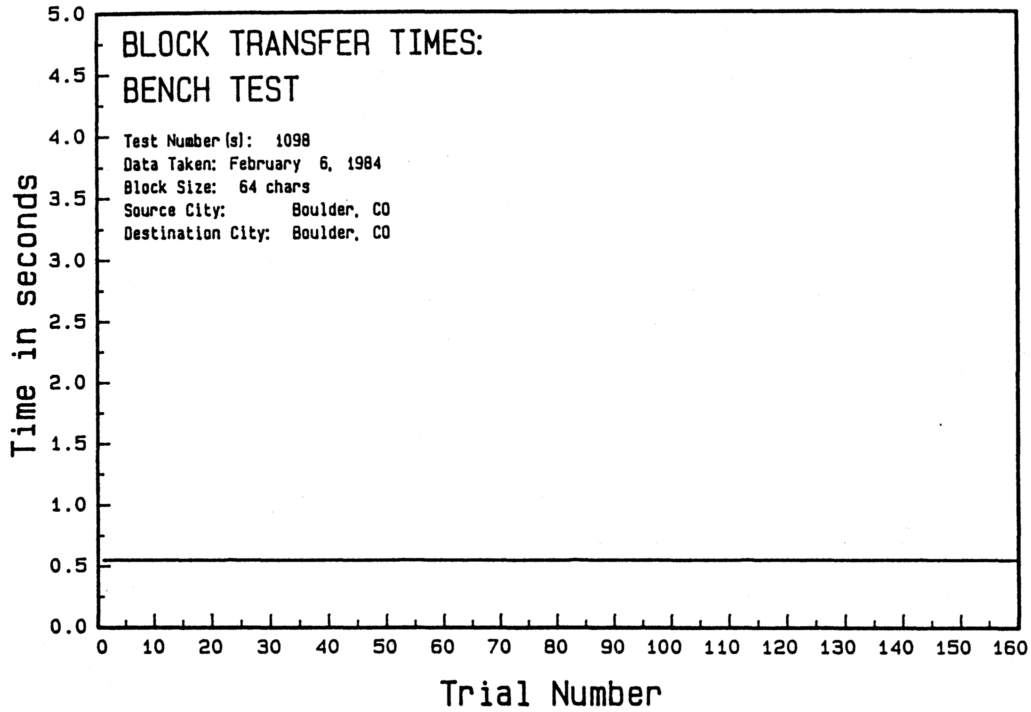
a. Local PDN Connection



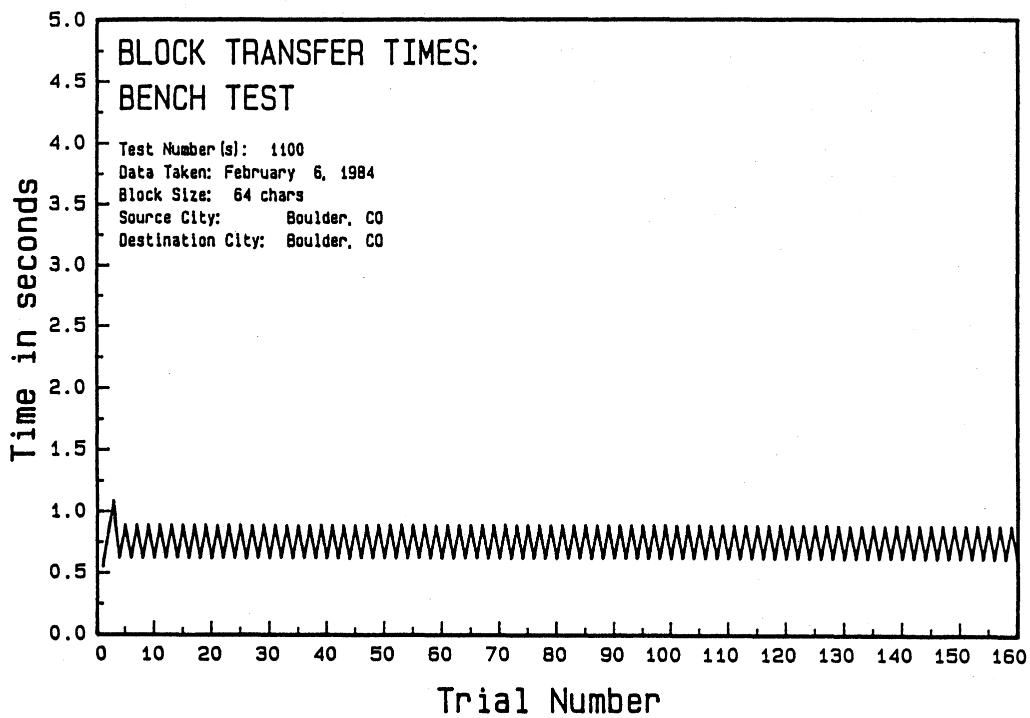
900	1198	1510	312	PDN A
930	1198	1550	352	PDN B
916	1198	1430	232	PDN C

b. Cross-Country PDN Connection

Figure E-2. Typical tests using PDN connections.

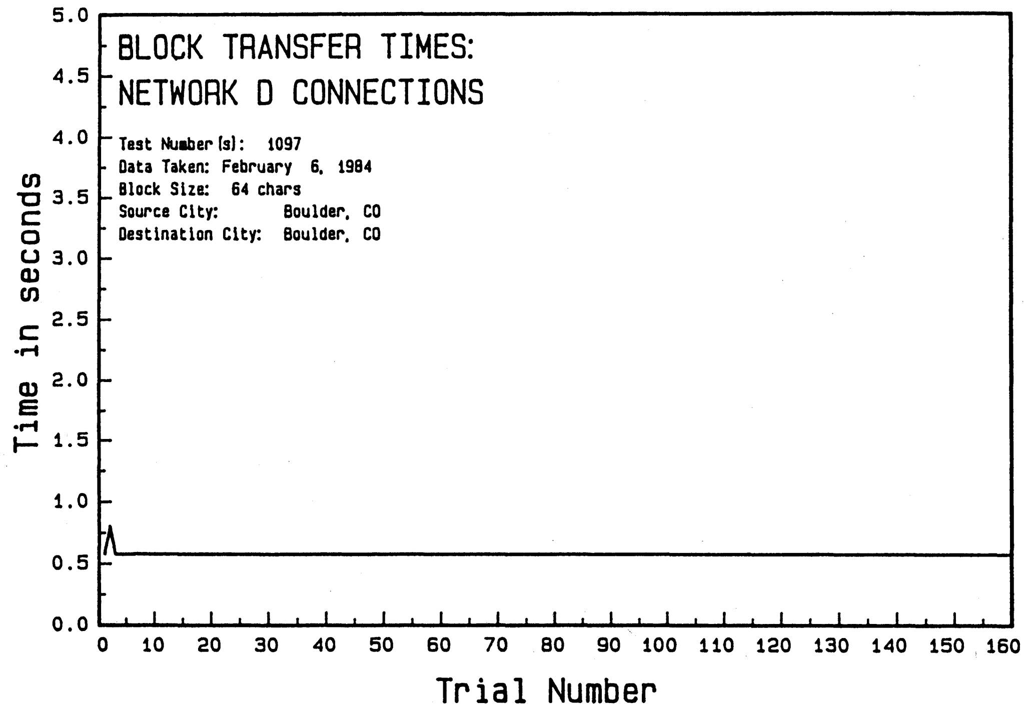


a. Low-Utilization Results

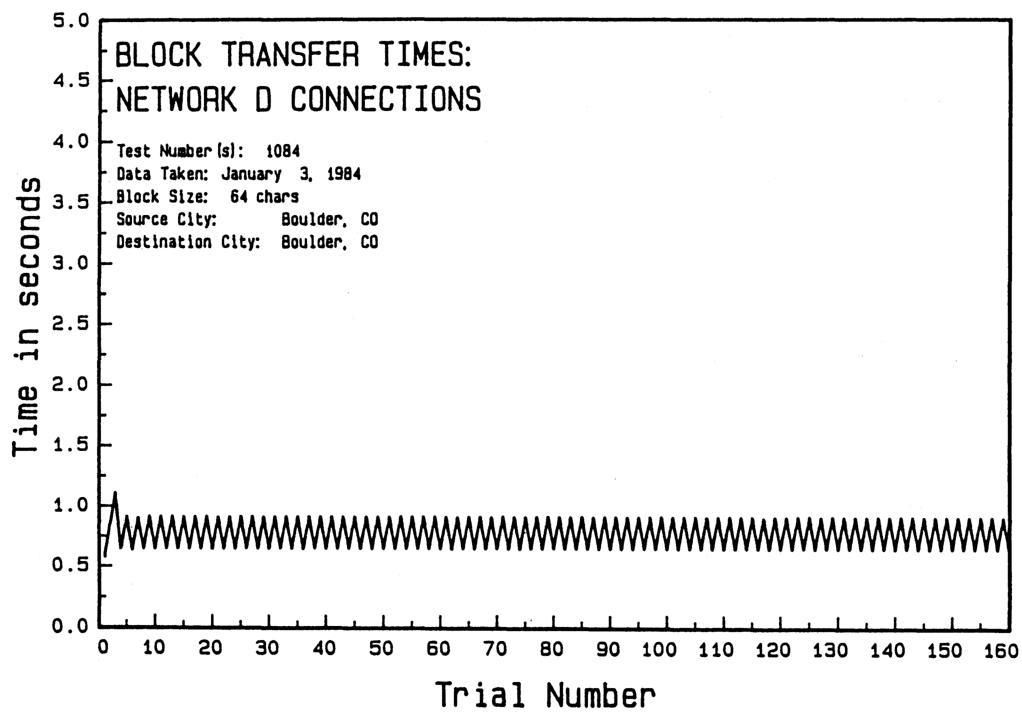


b. High-Utilization Results

Figure E-3. Block transfer times for hardwired bench tests.



a. Low-Utilization Results



b. High-Utilization Results

Figure E-4. Block transfer times for local dial-up connections.

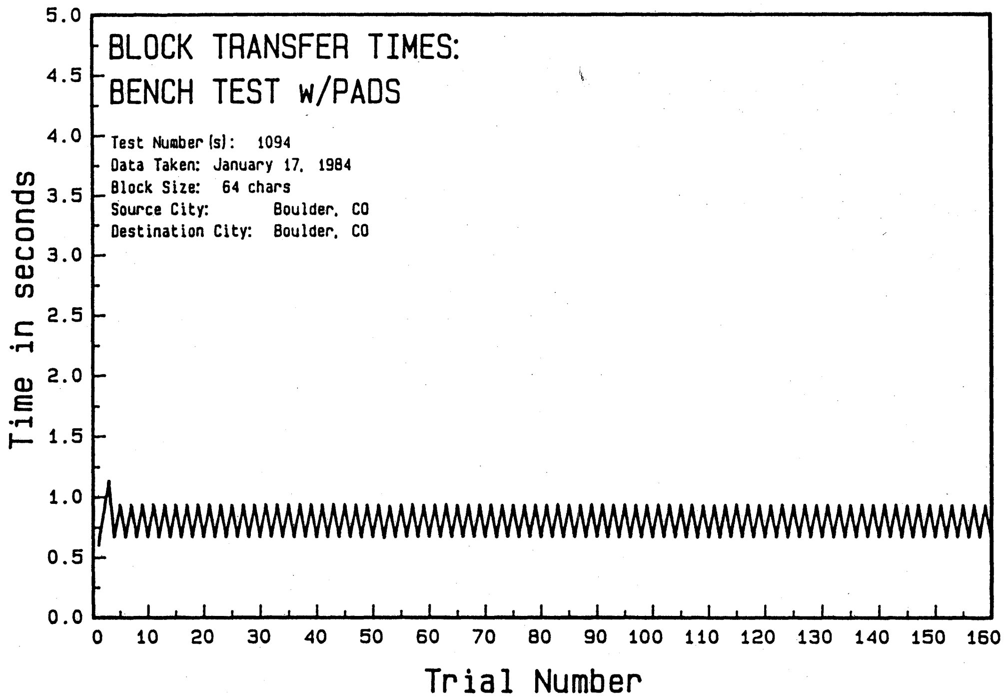


Figure E-5. Block transfer times for hardwired bench tests with X.25 PADs.

APPENDIX F: PLANNED AND ACTUAL TEST SEQUENCES

Prior to visiting a city for testing, a test plan was constructed in accordance with the Latin square design described in Section 3.5. All tests over a particular network during daytime hours were scheduled in a single time period (see Table 1 in Section 3 of this report). The numbers 0, 1, 2, and 3 were arbitrarily assigned to networks A, B, C, and D (or F), respectively. The network to be used in the first period in a given day was selected as the day of the month modulo 4. For example, on October 18, testing would start with network 2, followed in order by networks 3, 0, and 1. Four tests were scheduled in each time period. The first three were user information transfer tests for each of the block sizes specified in Table 1, and the last was an access-disengagement test. For each period, the order of user information transfer tests was randomized on the basis of block length.

When there were no failures, a user information transfer test required about 5 minutes and an access-disengagement test required about 40 minutes. By allowing 90 minutes for a complete set of four tests over a given network, some time generally remained to keep records, copy files to a floppy disk, and perform file and system maintenance. In addition, three time intervals in each day were allocated to transfer and consolidate extracted data files.

A set of four tests was scheduled in each of the two nighttime periods listed in Table 1. These tests were started automatically by a CRONTAB file (i.e., by the computer system clock). Each user information transfer test was allowed 1 hour, and the access-disengagement test was allowed 3 hours. To eliminate the need for an operator to switch between networks at the host site, all tests on a given night were conducted over a single network--the network used in the first time period of the day.

Schedules of planned tests and those actually conducted are shown in Tables F-1 through F-4 for individual cities. In actual test schedules, completed tests are shown with their chronological test number preceded by the code letter assigned to the network that was used. Block lengths are designated by s (64 characters), m (128 characters), and l (512 characters) on the left side of the table. Access-disengagement tests are indicated by "ovh-1". The fact that a test was completed and its number included in the table does not necessarily imply that the test was successful. A blank line in an actual test schedule indicates that the planned test was not completed.

A comparison of planned and actual test schedules clearly shows a higher percentage of completed tests from Washington and Denver. This may be attributed to an overall improvement in test techniques as the program progressed and to the correction of specific measurement system problems encountered in tests from Fort Worth and Seattle. Unattended nighttime tests show a substantially lower completion rate than operator-conducted daytime tests.

Table F-1. Test Schedules for Fort Worth, Texas

PROPOSED TEST SCHEDULE FOR DATA EXTRACTION
Fort Worth, Texas to Boulder, Colorado

Procedure	Local Time	Day - Dates Mon 10/17	Tue 10/18	Wed 10/19	Thu 10/20	Fri 10/21
File Transfer	0700 - 0830	- - -	<------	File Transfer	--------	------->
Day Test #1	0830 - 1000	Set-Up	Net 2	Net 3	Net 0	Net 1
Day Test #2	1000 - 1130	Set-Up	Net 3	Net 0	Net 1	Net 2
File Transfer	1130 - 1330	Dry Run	<------	File Transfer	--------	------->
Day Test #3	1330 - 1500	Net 3	Net 0	Net 1	Net 2	Pack-Up
Day Test #4	1500 - 1630	Net 0	Net 1	Net 2	Net 3	Leave
File Transfer	1630 - 1900	<-------	File Transfer	------	------>	- - -
Night Test #5	1900 - 0100	Net 1	Net 2	Net 3	Net 0	- - -
Night Test #6	0100 - 0700	Net 1	Net 2	Net 3	Net 0	- - -

ACTUAL TEST SCHEDULE

Procedure	Local Time	Day - Dates Mon 10/17	Tue 10/18	Wed 10/19	Thu 10/20	Fri 10/21
Day Test #1s	0830 - 1000	____	B 697	____	F 740	A 774
m		____	B 699	____	F 737	A 771
l		____	B 698	____	F 739	A 773
ovh-l		____	____	____	F 736	A 775
Day Test #2s	1000 - 1130	____	C 703	____	A 748	B 776
m		____	C 701	____	A 746	B 778
l		____	C 705	B 721	A 747	B 777
ovh-l		____	____	____	A 749	B 779
Day Test #3s	1330 - 1500	B 682	F 712	A 723	B 750	____
m		B 683	F 711	A 724	B 752	____
l		B 681	F 709	A 722	B 751	____
ovh-l		____	____	A 725	B 753	____
Day Test #4s	1500 - 1630	____	A 715	F 726	C 760	____
m		C 685	A 716	____	C 755	____
l		____	A 718	F 727	C 759	____
ovh-l		____	____	____	C 761	____
Night Test #5s	1900 - 0100	____	____	____	____	____
m		____	____	____	____	____
l		____	____	____	____	____
ovh-l		____	____	____	____	____
Night Test #6s	0100 - 0700	____	____	____	____	____
m		____	____	____	____	____
l		____	____	____	____	____
ovh-l		____	____	____	____	____

Table F-2. Test Schedules for Seattle, Washington

PROPOSED TEST SCHEDULE FOR DATA EXTRACTION
Seattle, Washington to Boulder, Colorado

Procedure	Local Time	Day - Dates Mon 11/28	 Tue 11/29	 Wed 11/30	 Thu 12/01	 Fri 12/02
File Transfer	0700 - 0830	- - -	<------ File Transfer -------->			
Day Test #1	0830 - 1000	Set-Up	Net 1	Net 2	Net 3	Net 0
Day Test #2	1000 - 1130	Set-Up	Net 2	Net 3	Net 0	Net 1
File Transfer	1130 - 1330	Dry Run	<------ File Transfer -------->			
Day Test #3	1330 - 1500	Net 2	Net 3	Net 0	Net 1	Pack-Up
Day Test #4	1500 - 1630	Net 3	Net 0	Net 1	Net 2	Leave
File Transfer	1630 - 1900	<------- File Transfer ------>				- - -
Night Test #5	1900 - 0100	Net 0	Net 1	Net 2	Net 3	- - -
Night Test #6	0100 - 0700	Net 0	Net 1	Net 2	Net 3	- - -

Procedure	Local Time	Day - Dates Mon 12/05	 Tue 12/06	 Wed 12/07	 Thu 12/08	 Fri 12/09
File Transfer	0700 - 0830	<-------------- File Transfer -------->				
Day Test #1	0830 - 1000	Net 3	Net 0	Net 1	Net 2	Net 3
Day Test #2	1000 - 1130	Net 0	Net 1	Net 2	Net 3	Net 0
File Transfer	1130 - 1330	<-------------- File Transfer -------->				
Day Test #3	1330 - 1500	Net 1	Net 2	Net 3	Net 0	Pack-Up
Day Test #4	1500 - 1630	Net 2	Net 3	Net 0	Net 1	Leave
File Transfer	1630 - 1900	<------- File Transfer ------>				- - -
Night Test #5	1900 - 0100	Net 3	Net 0	Net 1	Net 2	- - -
Night Test #6	0100 - 0700	Net 3	Net 0	Net 1	Net 2	- - -

ACTUAL TEST SCHEDULE

Procedure	Local Time	Day - Dates Thu 12/01	 Fri 12/02	 Mon 12/05	 Wed 12/07	 Thu 12/08
Day Test #1s	0830 - 1000	B 788	F 818	C 825	___	A 855
m		B 789	F 817	C 824	___	A 856
l		B 787	F 816	C 826	___	A 857
ovh-l		B 790	F 819	C 827	___	A 858
Day Test #2s	1000 - 1130	C 792	A 822	B 829	___	F 861
m		C 791	A 820	B 830	___	F 860
l		C 793	A 821	B 828	___	F 859
ovh-l		C 796	A 823	B 831	___	F 862
Day Test #3s	1330 - 1500	F 799	___	A 833	C 840	B 866
m		F 798	___	A 832	C 842	B 864
l		F 797	___	A 834	___	B 865
ovh-l		F 800	___	A 835	F 845	B 867
Day Test #4s	1500 - 1630	B 804	___	F 836	___	A 875
m		B 803	___	F 838	___	A 873
l		B 805	___	F 837	___	A 874
ovh-l		___	___	___	___	A 876
Night Test #5s	1900 - 0100	A 810	___	___	B 847	F 877
m		A 809	___	___	B 848	F 878
l		A 808	___	___	B 849	F 879
ovh-l		A 811	___	___	B 850	F 880
Night Test #6s	0100 - 0700	A 814	___	___	B 853	___
m		A 813	___	___	B 852	___
l		A 812	___	___	B 851	___
ovh-l		A 815	___	___	B 854	___

Table F-3. Test Schedules for Washington, DC

PROPOSED TEST SCHEDULE FOR DATA EXTRACTION
Washington, DC to Boulder, Colorado

Procedure	Local Time	Day - Dates Mon 12/12	Tue 12/13	Wed 12/14	Thu 12/15	Fri 12/16
File Transfer	0700 - 0830	<-------------- File Transfer -------->				
Day Test #1	0830 - 1000	Net 0	Net 1	Net 2	Net 3	Pack-Up
Day Test #2	1000 - 1130	Net 1	Net 2	Net 3	Net 0	Leave
File Transfer	1130 - 1330	<------ File Transfer ------->				- - -
Day Test #3	1330 - 1500	Net 2	Net 3	Net 0	Net 1	- - -
Day Test #4	1500 - 1630	Net 3	Net 0	Net 1	Net 2	- - -
File Transfer	1630 - 1900	<------ File Transfer ------->				- - -
Night Test #5	1900 - 0100	Net 0	Net 1	Net 2	Net 3	- - -
Night Test #6	0100 - 0700	Net 0	Net 1	Net 2	Net 3	- - -

ACTUAL TEST SCHEDULE

Procedure	Local Time	Day - Dates Sun 12/11	Mon 12/12	Tue 12/13	Wed 12/14	Thu 12/15
Day Test #1s	0830 - 1000	____	F 897	A 924	B 958	C 989
m		____	F 898	A 925	B 959	C 988
l		____	F 896	A 926	B 960	C 987
ovh-1		____	F 899	A 928	B 964	C 995
Day Test #2s	1000 - 1130	____	A 900	B 930	C 968	P 991
m		____	A 902	B 931	C 966	P 993
l		____	A 901	B 929	C 967	P 992
ovh-1		____	____	B 932	C 969	P 994
Day Test #3s	1330 - 1500	____	B 906	C 935	P 972	A 996&999
m		____	B 904	C 933	P 971	A 998
l		____	B 905	C 934	P 970	A1004
ovh-1		____	B 907	C 936	P 973	A 997
Day Test #4s	1500 - 1630	____	C 910	P 938	A 975	B1001
m		____	C 909	P 940	A 976	B1002
l		____	C 911&914	P 939	A 977	B1000
ovh-1		____	C 915	P 941	A 978	B1003
Night Test #5s	1900 - 0100	C 888	C 916	A 949	B 979	C1005
m		C 889	____	A 950	B 980	C1006
l		C 890	C 918	A 951	B 981	C1007
ovh-1		C 891	C 919	A 952	B 982	C1008
Night Test #6s	0100 - 0700	C 894	P 922	A 953	B 985	____
m		C 893	P 921	____	B 984	____
l		C 892	P 920	____	B 983	____
ovh-1		C 895	____	____	B 986	____

Table F-4. Test Schedules for Denver, Colorado

PROPOSED TEST SCHEDULE FOR DATA EXTRACTION
Denver, Colorado to Boulder, Colorado

Procedure	Local Time	Day - Dates Tue 12/27	Wed 12/28	Thu 12/29	Fri 12/30	
File Transfer	0700 - 0830	- - -	<--- File Transfer	--->		- - -
Day Test #1	0830 - 1000	Set-Up	Net 0	Net 2	Net 3	- - -
Day Test #2	1000 - 1130	Set-Up	Net 1	Net 3	Net 1&2	- - -
File Transfer	1130 - 1330	Dry Run	<--- File Transfer	--->		- - -
Day Test #3	1330 - 1500	Net 1	Net 2	Net 0	Pack-Up	- - -
Day Test #4	1500 - 1630	Net 0	Net 1	Net 2	Leave	- - -
File Transfer	1630 - 1900	<--- File Transfer	--->	- - -		- - -
Night Test #5	1900 - 0100	Net 3	Net 0	Net 1	- - -	- - -
Night Test #6	0100 - 0700	Net 3	Net 0	Net 2	- - -	- - -

ACTUAL TEST SCHEDULE

Procedure	Local Time	Day - Dates Tue 12/27	Wed 12/28	Thu 12/29	Fri 12/30	Fri 12/30
Day Test #1s	0830 - 1000		D1020	B1044	C1074	
m			D1021	B1045	C1072	
l			D1019	B1046	C1071	
ovh-l			D1022	B1047	C1075	
Day Test #2s	1000 - 1130		A1024	C1051	A1076	B1082
m			A1025	C1052	A1077	B1081
l			A1026	C1049	A1078	B1080
ovh-l			A1027	C1053		B1083
Day Test #3s	1330 - 1500		B1030	D1054		
m			B1029	D1055		
l			B1028	D1056		
ovh-l			B1031	D1057		
Day Test #4s	1500 - 1630		C1032	A1061		
m		F1009	C1033	A1060		
l		B1010	C1034	A1059		
ovh-l			C1035	A1062		
Night Test #5s	1900 - 0100	C1011		A1063		
m		C1012		A1064		
l				A1065		
ovh-l		C1014		A1066		
Night Test #6s	0100 - 0700	C1017	D1042	B1069		
m		C1016	D1041			
l		C1015	D1040	B1067		
ovh-l		C1018	D1043	B1070		

APPENDIX G: INDIVIDUAL TEST PARAMETER ESTIMATES

This appendix contains a set of tables that summarizes performance parameter estimates for each test listed in Tables 9 and 14 in Section 5. For each test and each parameter, the tables show the number of trials (indicated by the # symbol), the sample mean, and a sample standard deviation.[7] For the failure probability estimates, the sample mean is the sample failure probability $\hat{p}$, but the sample standard deviation is the estimated standard deviation of the number of failures under the assumption of independence, $[n\hat{p}(1-\hat{p})]^{1/2}$. The number of failures and the number of pairs of consecutive failures are also listed.

These items will enable confidence limits for the failure probability to be calculated using equation (A-36) or (A-44), pages 69-71, in Miles (1984). For the time parameters, no information on the degree of dependence of successive measurements is given in the tables, so confidence limits for the mean can be calculated only under the unrealistic assumption of independence. For example, for access time in Test 775, the standard error of the mean is $1.608/\sqrt{20} = 0.360$, so 95% confidence limits for the mean are

$$38.291 \pm 0.360 \times t_{19,0.025} = 38.291 \pm 0.360 \times 2.093 = 38.291 \pm 0.753,$$

or 37.5 and 39.0 seconds. Dependence tends to make the limits even wider. Appendix H should be consulted on the use of multiple tests to calculate realistic confidence limits.

The first three tables list access-disengagement test results, and the next nine tables list user information transfer test results. Columns at the left edge of each page list the test number and test conditions (city, network, day of the week, time period of the day, block length, flow control status, and signaling type). The columns are broken between cities.

References

Miles, M. J. (1984), Sample size and precision in communication performance measurement, NTIA Report 83-153, August (NTIS Order Number PB 85-114270).

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[7]Exceptions are User Fraction of Input/Output Time and User Information Bit Transfer Rate. Measured values of these parameters (listed in the tables) are based on only one trial per test.

Table G-1. Test Results for Access and Disengagement Delay Parameters

Test No.	Levels of Factors	Access Time					Source Disengagement Time					Destination Disengagement Time				
			Times		User Fractions			Times		User Fractions			Times		User Fractions	
		#	Mean	Std Dev	Mean	Std Dev	#	Mean	Std Dev	Mean	Std Dev	#	Mean	Std Dev	Mean	Std Dev
775	ftw A fri 1 L foff tone	20	38.291	1.608	0.0397	0.0199	19	14.038	1.179	0.0627	0.0070	20	4.790	0.955	0.1334	0.0387
779	ftw B fri 2 L f-on tone	17	39.540	0.711	0.0361	0.0067	17	12.892	0.489	0.0659	0.0032	17	2.810	0.138	0.2075	0.0134
790	sea B thu 2 L f-on tone	20	43.106	1.603	0.0345	0.0046	20	12.691	0.506	0.0791	0.0157	20	2.295	0.273	0.3220	0.0820
796	sea C thu 3 L foff tone	10	44.963	2.038	0.0351	0.0081	7	13.391	0.104	0.0622	0.0036	10	3.559	0.053	0.1613	0.0102
800	sea F thu 3 L foff tone	20	41.592	0.898	0.0357	0.0058	20	2.888	0.164	0.2550	0.0205	20	0.522	0.065	0.8997	0.0334
811	sea A thu 5 L foff tone	19	41.163	1.015	0.0373	0.0065	19	14.195	1.224	0.0668	0.0128	19	4.818	1.077	0.1521	0.0652
815	sea A fri 6 L foff tone	20	41.576	1.269	0.0352	0.0044	17	14.410	0.715	0.0598	0.0040	20	4.924	0.482	0.1225	0.0199
819	sea F fri 1 L foff tone	20	42.324	0.900	0.0339	0.0044	20	3.042	0.290	0.2511	0.0247	20	0.565	0.099	0.8809	0.0646
823	sea A fri 2 L foff tone	20	42.439	1.527	0.0339	0.0047	19	14.660	1.514	0.0618	0.0093	20	5.055	1.409	0.1389	0.0565
831	sea B mon 2 L f-on tone	18	41.711	1.826	0.0353	0.0059	17	12.006	0.663	0.0727	0.0042	18	2.055	0.373	0.2996	0.0396
835	sea A mon 3 L foff tone	15	42.954	1.325	0.0345	0.0053	15	15.379	1.644	0.0588	0.0079	15	5.064	1.402	0.1361	0.0484
845	sea F wed 3 L foff tone	18	42.073	0.900	0.0348	0.0062	18	2.917	0.312	0.2687	0.0230	18	0.600	0.130	0.8670	0.0383
850	sea B wed 5 L f-on tone	16	40.884	0.935	0.0366	0.0069	14	12.167	0.267	0.0713	0.0037	16	2.161	0.311	0.2816	0.0388
854	sea B thu 6 L f-on tone	15	41.438	1.878	0.0356	0.0067	12	11.993	0.454	0.0708	0.0029	15	2.025	0.219	0.2900	0.0364
858	sea A thu 1 L foff tone	20	42.284	1.339	0.0345	0.0053	17	15.592	1.196	0.0618	0.0132	20	5.890	1.108	0.1201	0.0427
867	sea B thu 3 L f-on tone	18	43.891	2.183	0.0334	0.0039	16	12.792	0.824	0.0711	0.0093	18	2.295	0.515	0.2889	0.0676
876	sea A thu 4 L foff tone	20	42.313	2.197	0.0350	0.0064	19	15.301	0.971	0.0613	0.0106	20	5.344	1.100	0.1386	0.0660
880	sea F thu 5 L foff tone	18	42.674	1.017	0.0346	0.0053	18	2.928	0.234	0.2625	0.0202	18	0.545	0.076	0.9208	0.0505
891	wdc C sun 5 L f-on puls	18	54.165	1.956	0.0282	0.0038	18	13.632	0.903	0.0655	0.0051	18	3.603	0.087	0.1728	0.0111
895	wdc C mon 6 L f-on puls	12	53.024	1.945	0.0294	0.0048	11	13.338	0.300	0.0653	0.0029	12	3.560	0.034	0.1697	0.0147
899	wdc F mon 1 L foff puls	19	53.362	0.980	0.0279	0.0047	19	4.113	0.334	0.2331	0.0428	19	0.938	0.189	0.7325	0.0866
907	wdc B mon 3 L f-on tone	18	43.863	1.624	0.0358	0.0060	17	12.828	0.709	0.0747	0.0148	18	2.097	0.338	0.3363	0.0777
915	wdc C mon 4 L f-on tone	17	45.477	2.350	0.0333	0.0046	16	14.058	1.373	0.0645	0.0057	17	3.730	0.216	0.1711	0.0148
919	wdc C mon 5 L f-on tone	17	44.434	2.050	0.0386	0.0273	17	13.434	0.357	0.0709	0.0117	17	3.663	0.257	0.1861	0.0314
928	wdc A tue 1 L foff tone	20	44.500	4.380	0.0332	0.0068	19	17.974	6.728	0.0576	0.0223	18	5.794	1.560	0.1311	0.0610
932	wdc B tue 2 L f-on tone	16	43.604	1.254	0.0333	0.0051	13	13.545	0.949	0.0647	0.0055	16	2.514	0.840	0.2676	0.0718
936	wdc C tue 3 L f-on tone	19	44.537	1.884	0.0328	0.0055	17	13.597	0.816	0.0692	0.0117	19	3.675	0.160	0.1818	0.0342
941	wdc D tue 4 L foff tone	20	35.622	0.918	0.0421	0.0128	20	3.088	0.352	0.2579	0.0334	20	0.563	0.077	0.9231	0.0256
952	wdc A tue 5 L f-on tone	20	39.813	1.625	0.0368	0.0043	17	14.894	1.082	0.0623	0.0106	20	5.234	0.964	0.1297	0.0385
964	wdc B wed 2 L f-on tone	19	43.455	0.985	0.0338	0.0053	16	13.033	0.467	0.0686	0.0047	19	2.614	0.147	0.2420	0.0195
969	wdc C wed 2 L f-on tone	12	44.265	1.396	0.0335	0.0056	11	13.390	0.685	0.0651	0.0046	12	3.261	0.354	0.1869	0.0226
973	wdc D wed 3 L foff tone	20	35.532	0.753	0.0408	0.0068	20	3.290	0.325	0.2721	0.0226	20	0.818	0.050	0.7615	0.0151
978	wdc A wed 4 L f-on tone	18	42.304	1.820	0.0351	0.0054	17	14.801	1.247	0.0676	0.0091	18	5.164	1.144	0.1498	0.0442
982	wdc B wed 5 L f-on tone	18	41.619	0.943	0.0372	0.0061	16	12.780	0.431	0.0748	0.0081	18	2.762	0.273	0.2566	0.0412
986	wdc B thu 6 L f-on tone	19	41.619	1.116	0.0365	0.0110	19	13.196	0.590	0.0723	0.0128	19	3.062	0.520	0.2260	0.0471
995	wdc C thu 3 L f-on tone	20	44.922	2.713	0.0322	0.0042	18	13.169	0.676	0.0681	0.0054	20	3.274	0.386	0.1945	0.0228
997	wdc A thu 3 L f-on tone	17	41.751	2.198	0.0356	0.0075	16	14.329	1.214	0.0666	0.0126	17	4.877	1.306	0.1552	0.0568
1003	wdc B thu 4 L f-on tone	18	44.363	1.094	0.0336	0.0054	17	13.574	0.690	0.0659	0.0057	18	2.742	0.202	0.2298	0.0190
1008	wdc C thu 5 L f-on tone	16	44.052	1.993	0.0336	0.0059	16	13.360	1.389	0.0753	0.0180	16	3.459	0.405	0.2105	0.0504
1014	den C tue 5 L f-on puls	17	55.388	1.991	0.0287	0.0107	17	13.122	0.246	0.0756	0.0126	17	3.460	0.277	0.2082	0.0344
1018	den C wed 6 L f-on puls	20	55.430	1.495	0.0268	0.0051	20	13.055	0.464	0.0729	0.0112	20	3.362	0.252	0.2033	0.0378
1027	den A wed 2 L f-on puls	19	48.643	0.778	0.0300	0.0042	18	13.832	1.374	0.0666	0.0119	19	5.022	1.170	0.1387	0.0569
1031	den B wed 3 L f-on puls	20	49.734	1.889	0.0308	0.0044	20	11.891	0.603	0.0755	0.0061	20	2.340	0.090	0.2691	0.0215
1035	den C wed 4 L f-on puls	18	55.471	1.969	0.0263	0.0039	17	13.495	0.785	0.0665	0.0061	18	3.379	0.225	0.1859	0.0163
1047	den B thu 1 L f-on puls	14	48.627	1.311	0.0302	0.0053	12	11.607	0.252	0.1018	0.0128	14	2.613	0.115	0.3506	0.0410
1053	den C thu 2 L f-on puls	6	53.776	0.705	0.0291	0.0068	4	13.448	0.129	0.0660	0.0105	6	3.483	0.238	0.1743	0.0340
1062	den A thu 4 L f-on puls	20	48.231	0.940	0.0308	0.0044	17	14.377	0.987	0.0630	0.0091	20	5.538	0.755	0.1231	0.0359
1066	den A thu 5 L f-on puls	20	47.737	0.989	0.0301	0.0039	16	13.933	0.713	0.0634	0.0047	20	5.337	0.682	0.1168	0.0327
1070	den B fri 6 L f-on puls	17	47.833	0.762	0.0303	0.0052	15	11.722	0.476	0.0772	0.0042	17	2.331	0.073	0.2688	0.0181
1075	den C fri 1 L f-on puls	15	54.913	1.623	0.0267	0.0051	11	13.212	0.358	0.0698	0.0092	15	3.364	0.221	0.1934	0.0276
1083	den B fri 2 L f-on puls	18	47.891	0.582	0.0314	0.0046	16	11.880	0.591	0.0768	0.0071	18	2.364	0.090	0.2723	0.0232

Table G-2. Test Results for Access Failure Parameters

Test No.	Levels of Factors	Incorrect Access #	Incorrect Access Fail	Incorrect Access Pairs	Incorrect Access Failure Prob.	Incorrect Access Standard Deviation	Access Outage #	Access Outage Fail	Access Outage Pairs	Access Outage Failure Prob.	Access Outage Standard Deviation	Access Denial #	Access Denial Fail	Access Denial Pairs	Access Denial Failure Prob.	Access Denial Standard Deviation
775	ftw A fri 1 L foff tone	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	0	0	0.000	0.000
779	ftw B fri 2 L f-on tone	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	3	2	0.150	1.597
790	sea B thu 2 L f-on tone	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	0	0	0.000	0.000
796	sea C thu 3 L foff tone	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	10	4	0.500	2.236
800	sea F thu 3 L foff tone	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	0	0	0.000	0.000
811	sea A thu 5 L foff tone	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	1	0	0.050	0.975
815	sea A fri 6 L foff tone	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	0	0	0.000	0.000
819	sea F fri 1 L foff tone	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	0	0	0.000	0.000
823	sea A fri 2 L foff tone	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	0	0	0.000	0.000
831	sea B mon 2 L f-on tone	20	0	0	0.000	0.000	20	1	0	0.050	0.975	20	1	0	0.050	0.975
835	sea A mon 3 L foff tone	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	5	4	0.250	1.936
845	sea F wed 3 L foff tone	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	2	0	0.100	1.342
850	sea B wed 5 L f-on tone	20	0	0	0.000	0.000	20	2	0	0.100	1.342	20	2	0	0.100	1.342
854	sea B thu 6 L f-on tone	20	0	0	0.000	0.000	20	3	0	0.150	1.597	20	2	0	0.100	1.342
858	sea A thu 1 L foff tone	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	0	0	0.000	0.000
867	sea B thu 3 L f-on tone	20	0	0	0.000	0.000	20	1	0	0.050	0.975	20	1	0	0.050	0.975
876	sea A thu 4 L foff tone	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	0	0	0.000	0.000
880	sea F thu 5 L foff tone	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	2	0	0.100	1.342
891	wdc C sun 5 L f-on puls	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	2	0	0.100	1.342
895	wdc C mon 6 L f-on puls	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	8	4	0.400	2.191
899	wdc F mon 1 L foff puls	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	1	0	0.050	0.975
907	wdc B mon 3 L f-on tone	20	0	0	0.000	0.000	20	1	0	0.050	0.975	20	1	0	0.050	0.975
915	wdc C mon 4 L f-on tone	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	3	0	0.150	1.597
919	wdc C mon 5 L f-on tone	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	3	0	0.150	1.597
928	wdc A tue 1 L foff tone	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	0	0	0.000	0.000
932	wdc B tue 2 L f-on tone	20	0	0	0.000	0.000	20	2	0	0.100	1.342	20	2	0	0.100	1.342
936	wdc C tue 3 L f-on tone	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	1	0	0.050	0.975
941	wdc D tue 4 L foff tone	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	0	0	0.000	0.000
952	wdc A tue 5 L f-on tone	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	0	0	0.000	0.000
964	wdc B wed 2 L f-on tone	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	1	0	0.050	0.975
969	wdc C wed 2 L f-on tone	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	8	4	0.400	2.191
973	wdc D wed 3 L foff tone	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	0	0	0.000	0.000
978	wdc A wed 4 L f-on tone	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	2	0	0.100	1.342
982	wdc B wed 5 L f-on tone	20	0	0	0.000	0.000	20	1	0	0.050	0.975	20	1	0	0.050	0.975
986	wdc B thu 6 L f-on tone	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	1	0	0.050	0.975
995	wdc C thu 3 L f-on tone	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	0	0	0.000	0.000
997	wdc A thu 3 L f-on tone	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	3	0	0.150	1.597
1003	wdc B thu 4 L f-on tone	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	2	0	0.100	1.342
1008	wdc C thu 5 L f-on tone	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	4	0	0.200	1.789
1014	den C tue 5 L f-on puls	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	3	0	0.150	1.597
1018	den C wed 6 L f-on puls	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	0	0	0.000	0.000
1027	den A wed 2 L f-on puls	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	1	0	0.050	0.975
1031	den B wed 3 L f-on puls	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	0	0	0.000	0.000
1035	den C wed 4 L f-on puls	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	2	0	0.100	1.342
1047	den B thu 1 L f-on puls	20	0	0	0.000	0.000	20	2	0	0.100	1.342	20	4	1	0.200	1.789
1053	den C thu 2 L f-on puls	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	14	10	0.700	2.049
1062	den A thu 4 L f-on puls	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	0	0	0.000	0.000
1066	den A thu 5 L f-on puls	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	0	0	0.000	0.000
1070	den B fri 6 L f-on puls	20	0	0	0.000	0.000	20	2	0	0.100	1.342	20	1	0	0.050	0.975
1075	den C fri 1 L f-on puls	20	0	0	0.000	0.000	20	0	0	0.000	0.000	20	5	0	0.250	1.936
1083	den B fri 2 L f-on puls	20	0	0	0.000	0.000	20	2	0	0.100	1.342	20	0	0	0.000	0.000

Table G-3. Test Results for Disengagement Failure Parameters

Test No.	Levels of Factors	Source Disengagement Denial					Destination Disengagement Denial				
		#	Fail	Pairs	Failure Prob.	Standard Deviation	#	Fail	Pairs	Failure Prob.	Standard Deviation
775	ftw A fri 1 L foff tone	20	1	0	0.050	0.975	20	0	0	0.000	0.000
779	ftw B fri 2 L f-on tone	17	0	0	0.000	0.000	17	0	0	0.000	0.000
790	sea B thu 2 L f-on tone	20	0	0	0.000	0.000	20	0	0	0.000	0.000
796	sea C thu 3 L foff tone	10	3	0	0.300	1.449	10	0	0	0.000	0.000
800	sea F thu 3 L foff tone	20	0	0	0.000	0.000	20	0	0	0.000	0.000
811	sea A thu 5 L foff tone	19	0	0	0.000	0.000	19	0	0	0.000	0.000
815	sea A fri 6 L foff tone	20	3	1	0.150	1.597	20	0	0	0.000	0.000
819	sea F fri 1 L foff tone	20	0	0	0.000	0.000	20	0	0	0.000	0.000
823	sea A fri 2 L foff tone	20	1	0	0.050	0.975	20	0	0	0.000	0.000
831	sea B mon 2 L f-on tone	18	1	0	0.056	0.972	18	0	0	0.000	0.000
835	sea A mon 3 L foff tone	15	0	0	0.000	0.000	15	0	0	0.000	0.000
845	sea F wed 3 L foff tone	18	0	0	0.000	0.000	18	0	0	0.000	0.000
850	sea B wed 5 L f-on tone	16	2	0	0.125	1.323	16	0	0	0.000	0.000
854	sea B thu 6 L f-on tone	15	3	0	0.200	1.549	15	0	0	0.000	0.000
858	sea A thu 1 L foff tone	20	3	0	0.150	1.597	20	0	0	0.000	0.000
867	sea B thu 3 L f-on tone	18	2	0	0.111	1.333	18	0	0	0.000	0.000
876	sea A thu 4 L foff tone	20	1	0	0.050	0.975	20	0	0	0.000	0.000
880	sea F thu 5 L foff tone	18	0	0	0.000	0.000	18	0	0	0.000	0.000
891	wdc C sun 5 L f-on puls	18	0	0	0.000	0.000	18	0	0	0.000	0.000
895	wdc C mon 6 L f-on puls	12	1	0	0.083	0.957	12	0	0	0.000	0.000
899	wdc F mon 1 L foff puls	19	0	0	0.000	0.000	19	0	0	0.000	0.000
907	wdc B mon 3 L f-on tone	18	1	0	0.056	0.972	18	0	0	0.000	0.000
915	wdc C mon 4 L f-on tone	17	1	0	0.059	0.970	17	0	0	0.000	0.000
919	wdc C mon 5 L f-on tone	17	0	0	0.000	0.000	17	0	0	0.000	0.000
928	wdc A tue 1 L foff tone	20	1	0	0.050	0.975	20	2	0	0.100	1.342
932	wdc B tue 2 L f-on tone	16	3	1	0.187	1.561	16	0	0	0.000	0.000
936	wdc C tue 3 L f-on tone	19	2	0	0.105	1.338	19	0	0	0.000	0.000
941	wdc D tue 4 L foff tone	20	0	0	0.000	0.000	20	0	0	0.000	0.000
952	wdc A tue 5 L f-on tone	20	3	0	0.150	1.597	20	0	0	0.000	0.000
964	wdc B wed 2 L f-on tone	19	3	0	0.158	1.589	19	0	0	0.000	0.000
969	wdc C wed 2 L f-on tone	12	1	0	0.083	0.957	12	0	0	0.000	0.000
973	wdc D wed 3 L foff tone	20	0	0	0.000	0.000	20	0	0	0.000	0.000
978	wdc A wed 4 L f-on tone	18	1	0	0.056	0.972	18	0	0	0.000	0.000
982	wdc B wed 5 L f-on tone	18	2	0	0.111	1.333	18	0	0	0.000	0.000
986	wdc B thu 6 L f-on tone	19	0	0	0.000	0.000	19	0	0	0.000	0.000
995	wdc C thu 3 L f-on tone	20	2	0	0.100	1.342	20	0	0	0.000	0.000
997	wdc A thu 3 L f-on tone	17	1	0	0.059	0.970	17	0	0	0.000	0.000
1003	wdc B thu 4 L f-on tone	18	1	0	0.056	0.972	18	0	0	0.000	0.000
1008	wdc C thu 5 L f-on tone	16	0	0	0.000	0.000	16	0	0	0.000	0.000
1014	den C tue 5 L f-on puls	17	0	0	0.000	0.000	17	0	0	0.000	0.000
1018	den C wed 6 L f-on puls	20	0	0	0.000	0.000	20	0	0	0.000	0.000
1027	den A wed 2 L f-on puls	19	1	0	0.053	0.973	19	0	0	0.000	0.000
1031	den B wed 3 L f-on puls	20	0	0	0.000	0.000	20	0	0	0.000	0.000
1035	den C wed 4 L f-on puls	18	1	0	0.056	0.972	18	0	0	0.000	0.000
1047	den B thu 1 L f-on puls	14	2	0	0.143	1.309	14	0	0	0.000	0.000
1053	den C thu 2 L f-on puls	6	2	1	0.333	1.155	6	0	0	0.000	0.000
1062	den A thu 4 L f-on puls	20	3	1	0.150	1.597	20	0	0	0.000	0.000
1066	den A thu 5 L f-on puls	20	4	2	0.200	1.789	20	0	0	0.000	0.000
1070	den B fri 6 L f-on puls	17	2	0	0.118	1.328	17	0	0	0.000	0.000
1075	den C fri 1 L f-on puls	15	4	0	0.267	1.713	15	0	0	0.000	0.000
1083	den B fri 2 L f-on puls	18	2	0	0.111	1.333	18	0	0	0.000	0.000

Table G-4. Test Results for Block Transfer Delay and Throughput Parameters: 64-Character Blocks

Test No.	Levels of Factors	Block Transfer Time #	Times Mean	Times Std Dev	User Fractions Mean	User Fractions Std Dev	Input/Output Time #	Times	User Fraction	User Information Bit Transfer #	Times	Rates
682	ftw B mon 3 S u-lo f-on tone	160	1.606	0.059	0.0829	0.0096						
697	ftw B tue 2 S u-lo f-on tone	160	1.739	0.106	0.0809	0.0177	1	158.449	0.9921	1	158.449	513.8
703	ftw C tue 3 S u-lo foff tone	160	1.656	0.208	0.0847	0.0187	1	158.573	0.9923	1	158.573	513.4
712	ftw F tue 3 S u-lo foff tone	160	0.583	0.017	0.0010	0.0133	1	158.356	0.9925	1	158.356	490.5
715	ftw A tue 4 S u-lo foff tone	160	1.604	0.098	0.0851	0.0148	1	158.347	0.9924	1	158.347	514.1
723	ftw A wed 3 S u-lo foff tone	160	1.618	0.116	0.0860	0.0173	1	158.684	0.9923	1	158.684	513.0
726	ftw F wed 4 S u-lo foff tone	160	0.582	0.005	0.0013	0.0164	1	158.916	0.9925	1	158.916	512.3
740	ftw F thu 1 S u-lo foff tone	160	0.581	0.002	0.0014	0.0176	1	158.480	0.9926	1	158.480	513.7
741	ftw C thu 1 S u-lo foff tone	160	1.590	0.063	0.0843	0.0121	1	158.541	0.9925	1	158.541	513.5
748	ftw A thu 2 S u-lo foff tone	160	1.619	0.106	0.0840	0.0119	1	158.318	0.9926	1	158.318	490.9
750	ftw B thu 3 S u-lo f-on tone	160	1.579	0.059	0.0843	0.0099	1	159.277	0.9924	1	159.277	511.1
760	ftw C thu 4 S u-lo foff tone	160	1.615	0.107	0.0831	0.0115	1	158.485	0.9925	1	158.485	513.7
774	ftw A fri 1 S u-lo foff tone	160	1.588	0.090	0.0849	0.0114	1	159.241	0.9925	1	159.241	511.2
776	ftw B fri 2 S u-lo f-on tone	160	1.629	0.080	0.0816	0.0082	1	158.652	0.9920	1	158.652	513.1
788	sea B thu 1 S u-lo f-on tone	160	1.658	0.088	0.0803	0.0081	1	158.926	0.9925	1	158.926	512.2
799	sea F thu 3 S u-lo foff tone	160	0.584	0.000	0.0014	0.0180	1	158.958	0.9925	1	158.958	512.1
804	sea B thu 4 S u-lo f-on tone	160	1.608	0.062	0.0829	0.0091	1	158.596	0.9925	1	158.596	513.3
810	sea A thu 5 S u-lo foff tone	160	1.557	0.087	0.0858	0.0107	1	158.679	0.9924	1	158.679	513.0
814	sea A fri 6 S u-lo foff tone	160	1.540	0.068	0.0860	0.0076	1	158.955	0.9926	1	158.955	512.1
818	sea F fri 1 S u-lo foff tone	159	0.582	0.002	0.0000	0.0000	1	159.168	0.9925	1	159.168	511.5
822	sea A fri 2 S u-lo foff tone	160	1.488	0.087	0.0891	0.0085	1	159.173	0.9925	1	159.173	509.8
829	sea B mon 2 S u-lo f-on tone	160	1.639	0.070	0.0808	0.0073	1	158.792	0.9926	1	158.792	512.7
833	sea A mon 3 S u-lo foff tone	160	1.660	0.109	0.0835	0.0164	1	159.203	0.9926	1	159.203	511.3
836	sea F mon 4 S u-lo foff tone	160	0.583	0.002	0.0014	0.0174	1	158.684	0.9915	1	158.684	513.0
847	sea B wed 5 S u-lo f-on tone	160	1.627	0.035	0.0815	0.0072	1	158.539	0.9926	1	158.539	513.5
853	sea B thu 6 S u-lo f-on tone	160	1.618	0.020	0.0818	0.0067	1	158.710	0.9926	1	158.710	512.9
855	sea A thu 1 S u-lo foff tone	160	1.699	0.171	0.0863	0.0253	1	158.770	0.9923	1	158.770	512.7
861	sea F thu 2 S u-lo foff tone	160	0.585	0.000	0.0000	0.0000	1	158.883	0.9906	1	158.883	512.4
866	sea B thu 3 S u-lo f-on tone	160	1.829	0.123	0.0880	0.0277	1	158.988	0.9926	1	158.988	512.0
875	sea A thu 4 S u-lo foff tone	160	1.477	0.089	0.0906	0.0101	1	159.051	0.9925	1	159.051	511.8
877	sea F thu 5 S u-lo foff tone	160	0.583	0.002	0.0012	0.0151	1	158.515	0.9922	1	158.515	513.6
888	wdc C sun 5 S u-lo f-on puls	160	1.465	0.036	0.0903	0.0075	1	158.626	0.9923	1	158.626	513.2
894	wdc C mon 6 S u-lo f-on puls	160	1.460	0.034	0.0906	0.0075	1	159.244	0.9920	1	159.244	511.2
897	wdc F mon 1 S u-lo foff puls	160	0.833	0.008	0.0015	0.0127	1	159.288	0.9926	1	159.288	511.1
898	wdc F mon 1 S u-lo foff puls	160	0.832	0.003	0.0001	0.0009	1	158.463	0.9925	1	158.463	513.7
900	wdc A mon 2 S u-lo foff puls	160	1.614	0.132	0.0858	0.0184	1	159.012	0.9925	1	159.012	512.0
906	wdc B mon 3 S u-lo f-on tone	160	1.726	0.272	0.0854	0.0246	1	158.663	0.9923	1	158.663	513.1
910	wdc C mon 4 S u-lo f-on tone	160	1.491	0.084	0.0894	0.0106	1	159.297	0.9915	1	159.297	511.0
916	wdc C mon 5 S u-lo f-on tone	160	1.484	0.076	0.0902	0.0107	1	159.302	0.9921	1	159.302	511.0
922	wdc D tue 6 S u-lo foff tone	160	0.581	0.003	0.0000	0.0000	1	158.521	0.9923	1	158.521	513.5
924	wdc A tue 1 S u-lo foff tone	106	4.222	0.924	0.0880	0.0247	1	159.097	0.9924	1	159.097	511.7
930	wdc B tue 2 S u-lo f-on tone	160	1.650	0.069	0.0806	0.0083	1	162.968	0.9651	1	162.968	450.8
935	wdc C tue 3 S u-lo f-on tone	160	1.530	0.162	0.0903	0.0190	1	158.821	0.9924	1	158.821	512.6
938	wdc D tue 4 S u-lo foff tone	160	0.578	0.007	0.0013	0.0159	1	159.188	0.9923	1	159.188	511.4
949	wdc A tue 5 S u-hi f-on tone	160	2.653	0.404	0.2158	0.0255	1	158.475	0.9925	1	158.475	513.7
958	wdc B wed 1 S u-hi f-on tone	160	2.403	0.334	0.2074	0.0303	1	89.202	0.4795	1	89.202	912.6
968	wdc C wed 2 S u-hi f-on tone	160	4.968	2.010	0.2157	0.0316	1	91.997	0.4644	1	91.997	884.9
972	wdc D wed 3 S u-hi foff tone	160	0.787	0.138	0.1742	0.0331	1	91.807	0.4654	1	91.807	886.7
975	wdc A wed 4 S u-hi f-on tone	160	2.787	0.529	0.2059	0.0339	1	86.155	0.4953	1	86.155	944.9
979	wdc B wed 5 S u-hi f-on tone	160	2.373	0.424	0.1974	0.0378	1	94.441	0.4522	1	94.441	862.0
985	wdc B thu 6 S u-hi f-on tone	160	2.682	0.531	0.1839	0.0429	1	97.122	0.4396	1	97.122	838.2
991	wdc D thu 2 S u-hi foff tone	160	0.782	0.135	0.1745	0.0330	1	107.556	0.3967	1	107.556	756.9
996	wdc A thu 3 S u-hi f-on tone	160	2.545	0.463	0.2036	0.0323	1	86.154	0.4957	1	86.154	944.9
999	wdc A thu 3 S u-hi f-on tone	160	2.561	0.427	0.2053	0.0325	1	94.437	0.4520	1	94.437	862.0
1001	wdc B thu 4 S u-hi f-on tone	160	3.061	0.698	0.2185	0.0253	1	93.716	0.4555	1	93.716	868.7
1005	wdc C thu 5 S u-hi f-on tone	160	2.557	0.690	0.2166	0.0247	1	88.635	0.4818	1	88.635	918.5
1011	den C tue 5 S u-hi f-on puls	160	3.056	0.739	0.2183	0.0258	1	88.234	0.4843	1	88.234	922.6
1017	den C wed 6 S u-hi f-on puls	160	2.545	0.737	0.2141	0.0258	1	88.487	0.4830	1	88.487	920.0
1020	den D wed 1 S u-hi foff puls	160	0.779	0.138	0.1761	0.0337	1	88.485	0.4825	1	88.485	920.0
1024	den A wed 2 S u-hi f-on puls	160	2.777	0.435	0.2166	0.0263	1	86.154	0.4958	1	86.154	944.9
1030	den B wed 3 S u-hi f-on puls	160	2.808	0.765	0.2167	0.0247	1	88.825	0.4807	1	88.825	916.5
1032	den C wed 4 S u-hi f-on puls	160	3.381	1.164	0.2162	0.0269	1	88.683	0.4816	1	88.683	918.0
1042	den D thu 6 S u-hi foff puls	160	0.779	0.135	0.1753	0.0333	1	89.703	0.4765	1	89.703	907.5
1044	den B thu 1 S u-hi f-on puls	160	2.641	0.733	0.2152	0.0252	1	86.154	0.4957	1	86.154	944.9
1051	den C thu 2 S u-hi f-on puls	160	7.036	3.100	0.2097	0.0312	1	88.513	0.4822	1	88.513	919.7
1054	den D thu 3 S u-hi foff puls	160	0.901	0.136	0.1895	0.0237	1	95.862	0.4453	1	95.862	849.2
1061	den A thu 4 S u-hi f-on puls	159	2.397	0.529	0.2136	0.0259	1	88.486	0.4825	1	88.486	919.9
1063	den A thu 5 S u-hi f-on puls	160	2.495	0.551	0.2144	0.0263	1	88.562	0.4823	1	88.562	919.2
1069	den B fri 6 S u-hi f-on puls	160	2.824	0.759	0.2170	0.0247	1	88.689	0.4814	1	88.689	917.9
1074	den C fri 1 S u-hi f-on puls	160	3.120	0.764	0.2183	0.0256	1	88.602	0.4817	1	88.602	918.8
1076	den A fri 2 S u-hi f-on puls	160	2.481	0.569	0.2138	0.0263	1	88.534	0.4824	1	88.534	919.5
1082	den B fri 2 S u-hi f-on puls	157	2.540	0.506	0.2161	0.0258	1	87.897	0.4858	1	87.897	915.8

Table G-5. Test Results for Bit Transfer Failure Parameters: 64-Character Blocks

Test No.	Levels of Factors	Bit Error #	Bit Error Fail	Bit Error Pairs	Bit Error Failure Prob.	Bit Error Standard Deviation	Extra Bit #	Extra Bit Fail	Extra Bit Pairs	Extra Bit Failure Prob.	Extra Bit Standard Deviation	Bit Loss #	Bit Loss Fail	Bit Loss Pairs	Bit Loss Failure Prob.	Bit Loss Standard Deviation
682	ftw B mon 3 S u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
697	ftw B tue 2 S u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
703	ftw C tue 3 S u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
712	ftw F tue 3 S u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
715	ftw A tue 4 S u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
723	ftw A wed 3 S u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
726	ftw F wed 4 S u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
740	ftw F thu 1 S u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
741	ftw C thu 1 S u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
748	ftw A thu 2 S u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
750	ftw B thu 3 S u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
760	ftw C thu 4 S u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
774	ftw A fri 1 S u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
776	ftw B fri 2 S u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
788	sea B thu 1 S u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
799	sea F thu 3 S u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
804	sea B thu 4 S u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
810	sea A thu 5 S u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
814	sea A fri 6 S u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
818	sea F fri 1 S u-lo foff tone	81656	0	0	0.000	0.000	81656	0	0	0.000	0.000	81920	264	263	0.003	16.222
822	sea A fri 2 S u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
829	sea B mon 2 S u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
833	sea A mon 3 S u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
836	sea F mon 4 S u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
847	sea B wed 5 S u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
853	sea B thu 6 S u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
855	sea A thu 1 S u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
861	sea F thu 2 S u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
866	sea B thu 3 S u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
875	sea A thu 4 S u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
877	sea F thu 5 S u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
888	wdc C sun 5 S u-lo f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
894	wdc C mon 6 S u-lo f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
897	wdc F mon 1 S u-lo foff puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
898	wdc F mon 1 S u-lo foff puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
900	wdc A mon 2 S u-lo foff puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
906	wdc B mon 3 S u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
910	wdc C mon 4 S u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
916	wdc C mon 5 S u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
922	wdc D tue 6 S u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
924	wdc A tue 1 S u-lo foff tone	73976	0	0	0.000	0.000	73976	0	0	0.000	0.000	81920	7944	7907	0.097	84.697
930	wdc B tue 2 S u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
935	wdc C tue 3 S u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
938	wdc D tue 4 S u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
949	wdc A tue 5 S u-hi f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
958	wdc B wed 1 S u-hi f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
968	wdc C wed 2 S u-hi f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
972	wdc D wed 3 S u-hi foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
975	wdc A wed 4 S u-hi f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
979	wdc B wed 5 S u-hi f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
985	wdc B thu 6 S u-hi f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
991	wdc D thu 2 S u-hi foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
996	wdc A thu 3 S u-hi f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
999	wdc A thu 3 S u-hi f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1001	wdc B thu 4 S u-hi f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1005	wdc C thu 5 S u-hi f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1011	den C tue 5 S u-hi f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1017	den C wed 6 S u-hi f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1020	den D wed 1 S u-hi foff puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1024	den A wed 2 S u-hi f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1030	den B wed 3 S u-hi f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1032	den C wed 4 S u-hi f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1042	den D thu 6 S u-hi foff puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1044	den B thu 1 S u-hi f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1051	den C thu 2 S u-hi f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1061	den A thu 4 S u-hi f-on puls	81912	0	0	0.000	0.000	81912	0	0	0.000	0.000	81920	8	7	0.000	2.828
1063	den A thu 5 S u-hi f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1069	den B fri 6 S u-hi f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1074	den C fri 1 S u-hi f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1076	den A fri 2 S u-hi f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1082	den B fri 2 S u-hi f-on puls	81008	0	0	0.000	0.000	81224	216	215	0.003	14.677	81920	912	911	0.011	30.031

Table G-6. Test Results for Block Transfer Failure and Availability Parameters: 64-Character Blocks

Test No.	Levels of Factors	Block Error #	Block Error Fail	Block Error Pairs	Block Error Failure Prob.	Block Error Standard Deviation	Extra Block #	Extra Block Fail	Extra Block Pairs	Extra Block Failure Prob.	Extra Block Standard Deviation	Block Loss #	Block Loss Fail	Block Loss Pairs	Block Loss Failure Prob.	Block Loss Standard Deviation	Transfer Denial #	Transfer Denial Fail	Transfer Denial Pairs	Transfer Denial Failure Prob.	Transfer Denial Standard Deviation
682	ftw B mon 3 S u-lo f-on tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
697	ftw B tue 2 S u-lo f-on tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
703	ftw C tue 3 S u-lo foff tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
712	ftw F tue 3 S u-lo foff tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
715	ftw A tue 4 S u-lo foff tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
723	ftw A wed 3 S u-lo foff tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
726	ftw F wed 4 S u-lo foff tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
740	ftw F thu 1 S u-lo foff tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
741	ftw C thu 1 S u-lo foff tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
748	ftw A thu 2 S u-lo foff tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
750	ftw B thu 3 S u-lo f-on tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
760	ftw C thu 4 S u-lo foff tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
774	ftw A fri 1 S u-lo foff tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
776	ftw B fri 2 S u-lo f-on tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
788	sea B thu 1 S u-lo f-on tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
799	sea F thu 3 S u-lo foff tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
804	sea B thu 4 S u-lo f-on tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
810	sea A thu 5 S u-lo foff tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
814	sea A fri 6 S u-lo foff tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
818	sea F fri 1 S u-lo foff tone	160	1	0	0.006	0.997	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	1	0	0.026	0.987
822	sea A fri 2 S u-lo foff tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
829	sea B mon 2 S u-lo f-on tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
833	sea A mon 3 S u-lo foff tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
836	sea F mon 4 S u-lo foff tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
847	sea B wed 5 S u-lo f-on tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
853	sea B thu 6 S u-lo f-on tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
855	sea A thu 1 S u-lo foff tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
861	sea F thu 2 S u-lo foff tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
866	sea B thu 3 S u-lo f-on tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
875	sea A thu 4 S u-lo foff tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
877	sea F thu 5 S u-lo foff tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
888	wdc C sun 5 S u-lo f-on puls	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
894	wdc C mon 6 S u-lo f-on puls	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
897	wdc F mon 1 S u-lo foff puls	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
898	wdc F mon 1 S u-lo foff puls	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
900	wdc A mon 2 S u-lo foff puls	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
906	wdc B mon 3 S u-lo f-on tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
910	wdc C mon 4 S u-lo f-on tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
916	wdc C mon 5 S u-lo f-on tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
922	wdc D tue 6 S u-lo foff tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
924	wdc A tue 1 S u-lo foff tone	154	48	10	0.312	5.748	154	0	0	0.000	0.000	160	6	0	0.037	2.403	39	33	27	0.846	2.253
930	wdc B tue 2 S u-lo f-on tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
935	wdc C tue 3 S u-lo f-on tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
938	wdc D tue 4 S u-lo foff tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
949	wdc A tue 5 S u-hi f-on tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
958	wdc B wed 1 S u-hi f-on tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
968	wdc C wed 2 S u-hi f-on tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
972	wdc D wed 3 S u-hi foff tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
975	wdc A wed 4 S u-hi f-on tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
979	wdc B wed 5 S u-hi f-on tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
985	wdc B thu 6 S u-hi f-on tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
991	wdc D thu 2 S u-hi foff tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
996	wdc A thu 3 S u-hi f-on tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
999	wdc A thu 3 S u-hi f-on tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
1001	wdc B thu 4 S u-hi f-on tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
1005	wdc C thu 5 S u-hi f-on tone	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
1011	den C tue 5 S u-hi f-on puls	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
1017	den C wed 6 S u-hi f-on puls	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
1020	den D wed 1 S u-hi foff puls	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
1024	den A wed 2 S u-hi f-on puls	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
1030	den B wed 3 S u-hi f-on puls	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
1032	den C wed 4 S u-hi f-on puls	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
1042	den D thu 6 S u-hi foff puls	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
1044	den B thu 1 S u-hi f-on puls	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
1051	den C thu 2 S u-hi f-on puls	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
1061	den A thu 4 S u-hi f-on puls	160	1	0	0.006	0.997	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
1063	den A thu 5 S u-hi f-on puls	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
1069	den B fri 6 S u-hi f-on puls	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
1074	den C fri 1 S u-hi f-on puls	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
1076	den A fri 2 S u-hi f-on puls	160	0	0	0.000	0.000	160	0	0	0.000	0.000	160	0	0	0.000	0.000	39	0	0	0.000	0.000
1082	den B fri 2 S u-hi f-on puls	159	2	0	0.013	1.405	159	0	0	0.000	0.000	160	1	0	0.006	0.997	39	1	0	0.026	0.987

Table G-7. Test Results for Block Transfer Delay and Throughput Parameters: 128-Character Blocks

Test No.	Levels of Factors	Block Transfer Time #	Times Mean	Times Std Dev	User Fractions Mean	User Fractions Std Dev	Input/Output Time #	Times	User Fractions	User Information Bit Transfer #	Times	Rates
683	ftw B mon 3 M u-lo f-on tone	80	2.818	0.089	0.0467	0.0055	1	157.663	0.6299	1	157.663	513.1
685	ftw C mon 4 M u-lo foff tone	80	2.880	0.033	0.0456	0.0052	1	157.886	0.6302	1	157.886	512.4
699	ftw B tue 2 M u-lo f-on tone	80	2.879	0.103	0.0457	0.0054	1	157.323	0.6283	1	157.323	514.2
701	ftw C tue 3 M u-lo foff tone	80	2.891	0.068	0.0455	0.0052	1	157.446	0.6290	1	157.446	513.8
711	ftw F tue 3 M u-lo foff tone	79	1.118	0.003	0.0014	0.0129	1	156.154	0.6271	1	156.154	515.0
716	ftw A tue 4 M u-lo foff tone	80	3.128	0.325	0.0435	0.0094	1	157.959	0.6306	1	157.959	512.1
724	ftw A wed 3 M u-lo foff tone	80	3.083	0.364	0.0447	0.0108	1	159.235	0.6229	1	159.235	508.0
737	ftw F thu 1 M u-lo foff tone	79	1.119	0.002	0.0000	0.0000	1	157.017	0.6330	1	157.017	510.1
746	ftw A thu 2 M u-lo foff tone	80	2.968	0.140	0.0443	0.0054	1	157.867	0.6297	1	157.867	512.4
752	ftw B thu 3 M u-lo f-on tone	80	2.824	0.216	0.0473	0.0079	1	157.491	0.6295	1	157.491	513.7
754	ftw A thu 4 M u-lo foff tone	71	3.602	0.598	0.0407	0.0156	1	158.474	0.6251	1	158.474	504.8
755	ftw C thu 4 M u-lo foff tone	80	2.879	0.028	0.0456	0.0052	1	157.428	0.6291	1	157.428	513.9
757	ftw D thu 4 M u-lo foff tone	80	1.117	0.003	0.0015	0.0132	1	157.085	0.6283	1	157.085	515.0
758	ftw F thu 4 M u-lo foff tone	80	1.119	0.004	0.0000	0.0000	1	157.968	0.6305	1	157.968	512.1
771	ftw A fri 1 M u-lo foff tone	80	2.947	0.155	0.0447	0.0055	1	157.262	0.6287	1	157.262	514.4
778	ftw B fri 2 M u-lo f-on tone	80	2.798	0.085	0.0470	0.0055	1	157.545	0.6292	1	157.545	513.5
789	sea B thu 1 M u-lo f-on tone	80	2.814	0.085	0.0467	0.0055	1	157.901	0.6294	1	157.901	512.3
798	sea F thu 3 M u-lo foff tone	79	1.121	0.002	0.0000	0.0000	1	157.794	0.6300	1	157.794	512.6
803	sea B thu 4 M u-lo f-on tone	80	2.751	0.053	0.0478	0.0055	1	157.111	0.6285	1	157.111	514.9
809	sea A thu 5 M u-lo foff tone	79	2.847	0.086	0.0462	0.0054	1	157.570	0.6293	1	157.570	513.3
813	sea A fri 6 M u-lo foff tone	80	2.837	0.118	0.0464	0.0055	1	157.749	0.6301	1	157.749	512.8
817	sea F fri 1 M u-lo foff tone	80	1.119	0.002	0.0000	0.0000	1	157.900	0.6305	1	157.900	512.3
820	sea A fri 2 M u-lo foff tone	80	2.750	0.108	0.0478	0.0057	1	157.670	0.6297	1	157.670	513.1
824	sea C mon 1 M u-lo foff tone	79	2.802	0.026	0.0469	0.0054	1	157.373	0.6290	1	157.373	513.9
830	sea B mon 2 M u-lo f-on tone	80	2.780	0.060	0.0473	0.0054	1	157.974	0.6306	1	157.974	512.1
832	sea A mon 3 M u-lo foff tone	80	2.752	0.127	0.0478	0.0057	1	157.450	0.6290	1	157.450	513.8
838	sea F mon 4 M u-lo foff tone	80	1.120	0.002	0.0000	0.0000	1	157.731	0.6299	1	157.731	512.9
848	sea B wed 5 M u-lo f-on tone	80	2.757	0.057	0.0477	0.0055	1	157.283	0.6282	1	157.283	514.3
852	sea B thu 6 M u-lo f-on tone	80	2.799	0.070	0.0469	0.0054	1	157.612	0.6296	1	157.612	513.3
856	sea A thu 1 M u-lo foff tone	80	3.075	0.216	0.0429	0.0056	1	157.702	0.6279	1	157.702	513.0
860	sea F thu 2 M u-lo foff tone	80	1.122	0.002	0.0000	0.0000	1	157.839	0.6302	1	157.839	512.5
864	sea B thu 3 M u-lo f-on tone	80	2.808	0.089	0.0468	0.0055	1	157.634	0.6296	1	157.634	513.2
873	sea A thu 4 M u-lo foff tone	80	2.889	0.103	0.0455	0.0054	1	157.914	0.6286	1	157.914	512.3
887	wdc C sun 4 M u-lo f-on puls	80	2.699	0.024	0.0487	0.0055	1	157.177	0.6285	1	157.177	514.7
889	wdc C sun 5 M u-lo f-on puls	80	2.709	0.041	0.0485	0.0055	1	157.247	0.6288	1	157.247	514.5
893	wdc C mon 6 M u-lo f-on puls	80	2.700	0.063	0.0487	0.0056	1	157.828	0.6303	1	157.828	512.6
902	wdc A mon 2 M u-lo foff puls	78	3.102	0.429	0.0436	0.0087	1	158.968	0.6259	1	158.968	505.8
904	wdc B mon 3 M u-lo f-on tone	80	2.815	0.157	0.0468	0.0057	1	157.524	0.6290	1	157.524	513.5
909	wdc C mon 4 M u-lo f-on tone	80	2.724	0.043	0.0482	0.0055	1	157.736	0.6300	1	157.736	512.9
921	wdc D tue 6 M u-lo foff tone	80	1.121	0.008	0.0000	0.0000	1	157.581	0.6295	1	157.581	513.4
925	wdc A tue 1 M u-lo foff tone	80	3.110	0.376	0.0442	0.0100	1	157.619	0.6295	1	157.619	513.2
931	wdc B tue 2 M u-lo f-on tone	80	2.880	0.086	0.0456	0.0053	1	157.755	0.6300	1	157.755	512.8
933	wdc C tue 3 M u-lo f-on tone	80	2.908	0.101	0.0452	0.0053	1	157.526	0.6296	1	157.526	513.5
940	wdc D tue 4 M u-lo foff tone	80	1.115	0.002	0.0000	0.0000	1	157.269	0.6289	1	157.269	514.4
950	wdc A tue 5 M u-hi f-on tone	80	3.701	0.429	0.0804	0.0151	1	104.310	0.2037	1	104.310	775.5
959	wdc B wed 1 M u-hi f-on tone	80	4.546	1.171	0.0998	0.0179	1	92.321	0.2301	1	92.321	876.2
971	wdc D wed 3 M u-hi foff tone	80	1.409	0.042	0.0930	0.0107	1	84.953	0.2499	1	84.953	952.2
976	wdc A wed 4 M u-hi f-on tone	80	4.175	0.756	0.0713	0.0166	1	120.935	0.1755	1	120.935	668.9
980	wdc B wed 5 M u-hi f-on tone	80	3.991	0.573	0.0941	0.0180	1	97.098	0.2189	1	97.098	833.1
984	wdc B thu 6 M u-hi f-on tone	80	3.936	0.510	0.0852	0.0187	1	103.381	0.2053	1	103.381	782.5
988	wdc C thu 1 M u-hi f-on tone	80	4.644	0.880	0.1042	0.0161	1	87.951	0.2415	1	87.951	919.8
993	wdc D thu 2 M u-hi foff tone	80	1.408	0.042	0.0931	0.0107	1	84.953	0.2500	1	84.953	952.2
998	wdc A thu 3 M u-hi f-on tone	80	3.914	0.577	0.0734	0.0149	1	111.796	0.1899	1	111.796	723.6
1002	wdc B thu 4 M u-hi f-on tone	80	5.785	1.429	0.1036	0.0152	1	90.847	0.2341	1	90.847	890.5
1006	wdc C thu 5 M u-hi f-on tone	80	5.048	1.355	0.1031	0.0161	1	89.543	0.2372	1	89.543	903.4
1009	den D tue 4 M u-hi foff puls	80	1.402	0.042	0.0935	0.0108	1	84.947	0.2503	1	84.947	952.3
1012	den C tue 5 M u-hi f-on puls	80	5.434	1.011	0.1046	0.0162	1	88.219	0.2407	1	88.219	917.0
1016	den C wed 6 M u-hi f-on puls	80	4.731	0.903	0.1059	0.0161	1	87.925	0.2415	1	87.925	920.1
1025	den A wed 2 M u-hi f-on puls	80	3.707	0.439	0.0981	0.0159	1	89.167	0.2383	1	89.167	907.2
1029	den B wed 3 M u-hi f-on puls	80	4.354	0.716	0.1008	0.0157	1	90.513	0.2345	1	90.513	893.8
1033	den C wed 4 M u-hi f-on puls	80	6.786	1.459	0.1041	0.0167	1	89.923	0.2362	1	89.923	899.6
1041	den D thu 6 M u-hi foff puls	80	1.403	0.042	0.0934	0.0108	1	84.953	0.2504	1	84.953	952.2
1045	den B thu 1 M u-hi f-on puls	80	4.082	0.554	0.0978	0.0153	1	90.662	0.2342	1	90.662	892.3
1052	den C thu 2 M u-hi f-on puls	80	9.173	2.781	0.1030	0.0180	1	93.790	0.2264	1	93.790	862.5
1060	den A thu 4 M u-hi f-on puls	80	3.660	0.413	0.0999	0.0167	1	88.822	0.2391	1	88.822	910.8
1064	den A thu 5 M u-hi f-on puls	79	3.685	0.425	0.1016	0.0164	1	88.125	0.2411	1	88.125	917.9
1072	den C fri 1 M u-hi f-on puls	80	5.169	0.945	0.1039	0.0162	1	87.933	0.2415	1	87.933	920.0
1077	den A fri 2 M u-hi f-on puls	80	3.671	0.451	0.0981	0.0170	1	91.354	0.2325	1	91.354	885.5
1081	den B fri 2 M u-hi f-on puls	80	3.871	0.531	0.0969	0.0158	1	91.500	0.2322	1	91.500	884.1

Table G-8. Test Results for Bit Transfer Failure Parameters: 128-Character Blocks

Test No.	Levels of Factors	Bit Error #	Bit Error Fail	Bit Error Pairs	Bit Error Failure Prob.	Bit Error Standard Deviation	Extra Bit #	Extra Bit Fail	Extra Bit Pairs	Extra Bit Failure Prob.	Extra Bit Standard Deviation	Bit Loss #	Bit Loss Fail	Bit Loss Pairs	Bit Loss Failure Prob.	Bit Loss Standard Deviation
683	ftw B mon 3 M u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
685	ftw C mon 4 M u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
699	ftw B tue 2 M u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
701	ftw C tue 3 M u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
711	ftw F tue 3 M u-lo foff tone	81448	11	5	0.000	3.316	81448	0	0	0.000	0.000	81920	472	471	0.006	21.663
716	ftw A tue 4 M u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
724	ftw A wed 3 M u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
737	ftw F thu 1 M u-lo foff tone	81120	0	0	0.000	0.000	81120	0	0	0.000	0.000	81920	800	799	0.010	28.146
746	ftw A thu 2 M u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
752	ftw B thu 3 M u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
754	ftw A thu 4 M u-lo foff tone	81016	0	0	0.000	0.000	81016	0	0	0.000	0.000	81920	904	898	0.011	29.900
755	ftw C thu 4 M u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
757	ftw D thu 4 M u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
758	ftw F thu 4 M u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
771	ftw A fri 1 M u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
778	ftw B fri 2 M u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
789	sea B thu 1 M u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
798	sea F thu 3 M u-lo foff tone	81920	6	1	0.000	2.449	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
803	sea B thu 4 M u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
809	sea A thu 5 M u-lo foff tone	81912	0	0	0.000	0.000	81912	0	0	0.000	0.000	81920	8	7	0.000	2.828
813	sea A fri 6 M u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
817	sea F fri 1 M u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
820	sea A fri 2 M u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
824	sea C mon 1 M u-lo foff tone	81896	0	0	0.000	0.000	81896	0	0	0.000	0.000	81920	24	23	0.000	4.898
830	sea B mon 2 M u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
832	sea A mon 3 M u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
838	sea F mon 4 M u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
848	sea B wed 5 M u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
852	sea B thu 6 M u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
856	sea A thu 1 M u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
860	sea F thu 2 M u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
864	sea B thu 3 M u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
873	sea A thu 4 M u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
887	wdc C sun 4 M u-lo f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
889	wdc C sun 5 M u-lo f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
893	wdc C mon 6 M u-lo f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
902	wdc A mon 2 M u-lo foff puls	81432	0	0	0.000	0.000	81432	0	0	0.000	0.000	81920	488	487	0.006	22.025
904	wdc B mon 3 M u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
909	wdc C mon 4 M u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
921	wdc D tue 6 M u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
925	wdc A tue 1 M u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
931	wdc B tue 2 M u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
933	wdc C tue 3 M u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
940	wdc D tue 4 M u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
950	wdc A tue 5 M u-hi f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
959	wdc B wed 1 M u-hi f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
971	wdc D wed 3 M u-hi foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
976	wdc A wed 4 M u-hi f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
980	wdc B wed 5 M u-hi f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
984	wdc B thu 6 M u-hi f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
988	wdc C thu 1 M u-hi f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
993	wdc D thu 2 M u-hi foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
998	wdc A thu 3 M u-hi f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1002	wdc B thu 4 M u-hi f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1006	wdc C thu 5 M u-hi f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1009	den D tue 4 M u-hi foff puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1012	den C tue 5 M u-hi f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1016	den C wed 6 M u-hi f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1025	den A wed 2 M u-hi f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1029	den B wed 3 M u-hi f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1033	den C wed 4 M u-hi f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1041	den D thu 6 M u-hi foff puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1045	den B thu 1 M u-hi f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1052	den C thu 2 M u-hi f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1060	den A thu 4 M u-hi f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1064	den A thu 5 M u-hi f-on puls	81920	4	2	0.000	2.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1072	den C fri 1 M u-hi f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1077	den A fri 2 M u-hi f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1081	den B fri 2 M u-hi f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000

Table G-9. Test Results for Block Transfer Failure and Availability Parameters: 128-Character Blocks

Test No.	Levels of Factors	Block Error #	Fail	Pairs	Failure Prob.	Standard Deviation	Extra Block #	Fail	Pairs	Failure Prob.	Standard Deviation	Block Loss #	Fail	Pairs	Failure Prob.	Standard Deviation	Transfer Denial #	Fail	Pairs	Failure Prob.	Standard Deviation
683	ftw B mon 3 M u-lo f-on tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
685	ftw C mon 4 M u-lo foff tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
699	ftw B tue 2 M u-lo f-on tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
701	ftw C tue 3 M u-lo foff tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
711	ftw F tue 3 M u-lo foff tone	80	1	0	0.012	0.994	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	1	0	0.026	0.987
716	ftw A tue 4 M u-lo foff tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
724	ftw A wed 3 M u-lo foff tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
737	ftw F,thu 1 M u-lo foff tone	80	1	0	0.012	0.994	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	1	0	0.026	0.987
746	ftw A thu 2 M u-lo foff tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
752	ftw B thu 3 M u-lo f-on tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
754	ftw A thu 4 M u-lo foff tone	80	9	3	0.112	2.826	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	5	0	0.128	2.088
755	ftw C thu 4 M u-lo foff tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
757	ftw D thu 4 M u-lo foff tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
758	ftw F thu 4 M u-lo foff tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
771	ftw A fri 1 M u-lo foff tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
778	ftw B fri 2 M u-lo f-on tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
789	sea B thu 1 M u-lo f-on tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
798	sea F thu 3 M u-lo foff tone	80	1	0	0.012	0.994	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
803	sea B thu 4 M u-lo f-on tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
809	sea A thu 5 M u-lo foff tone	80	1	0	0.012	0.994	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
813	sea A fri 6 M u-lo foff tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
817	sea F fri 1 M u-lo foff tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
820	sea A fri 2 M u-lo foff tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
824	sea C mon 1 M u-lo foff tone	80	1	0	0.012	0.994	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	1	0	0.026	0.987
830	sea B mon 2 M u-lo f-on tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
832	sea A mon 3 M u-lo foff tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
838	sea F mon 4 M u-lo foff tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
848	sea B wed 5 M u-lo f-on tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
852	sea B thu 6 M u-lo f-on tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
856	sea A thu 1 M u-lo foff tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
860	sea F thu 2 M u-lo foff tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
864	sea B thu 3 M u-lo f-on tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
873	sea A thu 4 M u-lo foff tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
887	wdc C sun 4 M u-lo f-on puls	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
889	wdc C sun 5 M u-lo f-on puls	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
893	wdc C mon 6 M u-lo f-on puls	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
902	wdc A mon 2 M u-lo foff puls	80	2	1	0.025	1.396	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	2	1	0.051	1.377
904	wdc B mon 3 M u-lo f-on tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
909	wdc C mon 4 M u-lo f-on tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
921	wdc D tue 6 M u-lo foff tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
925	wdc A tue 1 M u-lo foff tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
931	wdc B tue 2 M u-lo f-on tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
933	wdc C tue 3 M u-lo f-on tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
940	wdc D tue 4 M u-lo foff tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
950	wdc A tue 5 M u-hi f-on tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
959	wdc B wed 1 M u-hi f-on tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
971	wdc D wed 3 M u-hi foff tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
976	wdc A wed 4 M u-hi f-on tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
980	wdc B wed 5 M u-hi f-on tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
984	wdc B thu 6 M u-hi f-on tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
988	wdc C thu 1 M u-hi f-on tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
993	wdc D thu 2 M u-hi foff tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
998	wdc A thu 3 M u-hi f-on tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
1002	wdc B thu 4 M u-hi f-on tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
1006	wdc C thu 5 M u-hi f-on tone	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
1009	den D tue 4 M u-hi foff puls	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
1012	den C tue 5 M u-hi f-on puls	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
1016	den C wed 6 M u-hi f-on puls	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
1025	den A wed 2 M u-hi f-on puls	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
1029	den B wed 3 M u-hi f-on puls	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
1033	den C wed 4 M u-hi f-on puls	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
1041	den D thu 6 M u-hi foff puls	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
1045	den B thu 1 M u-hi f-on puls	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
1052	den C thu 2 M u-hi f-on puls	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
1060	den A thu 4 M u-hi f-on puls	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
1064	den A thu 5 M u-hi f-on puls	80	1	0	0.012	0.994	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
1072	den C fri 1 M u-hi f-on puls	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
1077	den A fri 2 M u-hi f-on puls	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000
1081	den B fri 2 M u-hi f-on puls	80	0	0	0.000	0.000	80	0	0	0.000	0.000	80	0	0	0.000	0.000	39	0	0	0.000	0.000

Table G-10. Test Results for Block Transfer Delay and Throughput Parameters: 512-Character Blocks

Test No.	Levels of Factors	Block Transfer Time					Input/Output Time			User Information Bit Transfer		
			Times		User Fractions			Times	User Fractions		Times	Rates
		#	Mean	Std Dev	Mean	Std Dev	#			#		
680	ftw A mon 3 L u-lo foff tone	20	6.518	0.301	0.0194	0.0046	1	94.989	0.2289	1	94.989	819.3
681	ftw B mon 3 L u-lo f-on tone	20	6.252	0.353	0.0203	0.0049	1	94.641	0.2281	1	94.641	822.3
698	ftw B tue 2 L u-lo f-on tone	20	6.214	0.123	0.0204	0.0048	1	94.819	0.2296	1	94.819	820.8
705	ftw C tue 3 L u-lo foff tone	20	6.221	0.109	0.0203	0.0048	1	94.444	0.2265	1	94.444	824.0
709	ftw F tue 3 L u-lo foff tone	20	4.323	0.003	0.0011	0.0047	1	94.377	0.2260	1	94.377	824.6
718	ftw A tue 4 L u-lo foff tone	11	7.032	0.529	0.0174	0.0059	1	94.154	0.2227	1	94.154	781.2
721	ftw B wed 2 L u-lo f-on tone	20	6.571	0.164	0.0193	0.0046	1	95.069	0.2318	1	95.069	818.6
722	ftw A wed 3 L u-lo foff tone	13	6.937	0.455	0.0161	0.0072	1	95.643	0.2277	1	95.643	798.6
727	ftw F wed 4 L u-lo foff tone	20	4.324	0.004	0.0000	0.0000	1	94.488	0.2271	1	94.488	823.6
739	ftw F thu 1 L u-lo foff tone	20	4.323	0.003	0.0000	0.0000	1	94.888	0.2301	1	94.888	820.2
743	ftw C thu 1 L u-lo foff tone	20	6.309	0.425	0.0201	0.0049	1	96.097	0.2189	1	96.097	809.8
747	ftw A thu 2 L u-lo foff tone	18	6.807	0.378	0.0185	0.0048	1	94.614	0.2249	1	94.614	808.8
751	ftw B thu 3 L u-lo f-on tone	20	6.371	0.267	0.0199	0.0047	1	95.455	0.2235	1	95.455	815.3
759	ftw C thu 4 L u-lo foff tone	20	6.201	0.082	0.0204	0.0048	1	94.696	0.2286	1	94.696	821.8
773	ftw A fri 1 L u-lo foff tone	18	6.584	0.319	0.0192	0.0049	1	95.013	0.2313	1	95.013	815.1
777	ftw B fri 2 L u-lo f-on tone	20	6.221	0.111	0.0203	0.0048	1	94.339	0.2256	1	94.339	824.9
787	sea B thu 1 L u-lo f-on tone	20	6.363	0.461	0.0199	0.0049	1	94.408	0.2262	1	94.408	824.3
797	sea F thu 3 L u-lo foff tone	20	4.325	0.004	0.0000	0.0000	1	94.698	0.2287	1	94.698	821.8
805	sea B thu 4 L u-lo f-on tone	20	6.060	0.064	0.0208	0.0049	1	94.848	0.2300	1	94.848	820.5
808	sea A thu 5 L u-lo foff tone	19	6.281	0.332	0.0201	0.0050	1	94.944	0.2292	1	94.944	819.1
812	sea A fri 6 L u-lo foff tone	19	6.710	0.279	0.0188	0.0046	1	94.910	0.2304	1	94.910	819.0
816	sea F fri 1 L u-lo foff tone	20	4.323	0.003	0.0000	0.0000	1	95.091	0.2320	1	95.091	818.4
821	sea A fri 2 L u-lo foff tone	19	6.463	0.316	0.0196	0.0048	1	94.440	0.2251	1	94.440	820.2
826	sea C mon 1 L u-lo foff tone	20	6.100	0.058	0.0207	0.0049	1	94.363	0.2254	1	94.363	824.7
828	sea B mon 2 L u-lo f-on tone	20	6.117	0.075	0.0207	0.0049	1	95.095	0.2311	1	95.095	818.4
834	sea A mon 3 L u-lo foff tone	18	6.850	0.355	0.0183	0.0047	1	95.186	0.2251	1	95.186	813.9
837	sea F mon 4 L u-lo foff tone	20	4.325	0.004	0.0000	0.0000	1	94.668	0.2285	1	94.668	822.1
849	sea B wed 5 L u-lo f-on tone	20	6.135	0.053	0.0206	0.0049	1	94.769	0.2289	1	94.769	821.2
851	sea B thu 6 L u-lo f-on tone	20	6.071	0.066	0.0208	0.0049	1	94.832	0.2291	1	94.832	820.7
857	sea A thu 1 L u-lo foff tone	20	6.291	0.267	0.0201	0.0048	1	95.049	0.2286	1	95.049	818.8
859	sea F thu 2 L u-lo foff tone	20	4.325	0.004	0.0000	0.0000	1	94.921	0.2305	1	94.921	819.9
865	sea B thu 3 L u-lo f-on tone	20	6.314	0.684	0.0201	0.0050	1	97.721	0.2197	1	97.721	796.4
874	sea A thu 4 L u-lo foff tone	14	6.907	0.366	0.0180	0.0053	1	94.421	0.2264	1	94.421	808.7
890	wdc C sun 5 L u-lo f-on puls	20	6.533	0.532	0.0194	0.0048	1	95.363	0.2294	1	95.363	816.1
892	wdc C mon 6 L u-lo f-on puls	20	5.998	0.031	0.0211	0.0050	1	94.710	0.2285	1	94.710	821.7
896	wdc F mon 1 L u-lo foff puls	20	4.573	0.003	0.0015	0.0065	1	94.442	0.2266	1	94.442	824.0
901	wdc A mon 2 L u-lo foff puls	12	8.210	2.377	0.0091	0.0087	1	96.878	0.2246	1	96.878	793.2
905	wdc B mon 3 L u-lo f-on tone	20	6.127	0.088	0.0206	0.0049	1	94.709	0.2284	1	94.709	821.7
911	wdc C mon 4 L u-lo f-on tone	20	26.186	8.544	0.0195	0.0092	1	107.241	0.1973	1	107.241	725.7
914	wdc C mon 4 L u-lo f-on tone	20	6.040	0.061	0.0209	0.0049	1	94.668	0.2285	1	94.668	822.1
918	wdc C mon 5 L u-lo f-on tone	20	6.224	0.176	0.0203	0.0048	1	94.609	0.2277	1	94.609	822.6
920	wdc D tue 6 L u-lo foff tone	20	4.322	0.002	0.0000	0.0000	1	95.103	0.2318	1	95.103	818.3
926	wdc A tue 1 L u-lo foff tone	16	6.766	0.373	0.0185	0.0050	1	94.837	0.2226	1	94.837	802.1
929	wdc B tue 2 L u-lo f-on tone	20	6.039	0.050	0.0209	0.0049	1	94.960	0.2305	1	94.960	819.5
934	wdc C tue 3 L u-lo f-on tone	20	6.388	0.429	0.0198	0.0048	1	94.743	0.2271	1	94.743	821.4
939	wdc D tue 4 L u-lo foff tone	20	4.319	0.004	0.0000	0.0000	1	94.794	0.2294	1	94.794	821.0
951	wdc A tue 5 L u-hi f-on tone	20	7.212	0.489	0.0174	0.0042	1	86.692	0.0590	1	86.692	897.7
953	wdc A wed 6 L u-hi f-on tone	20	7.126	0.482	0.0177	0.0043	1	84.561	0.0604	1	84.561	920.3
960	wdc B wed 1 L u-hi f-on tone	20	7.497	0.897	0.0186	0.0058	1	84.063	0.0609	1	84.063	925.8
967	wdc C wed 2 L u-hi f-on tone	20	7.479	0.794	0.0174	0.0047	1	83.727	0.0611	1	83.727	929.5
970	wdc D wed 3 L u-hi foff tone	20	4.476	0.037	0.0282	0.0066	1	81.251	0.0629	1	81.251	957.8
977	wdc A wed 4 L u-hi f-on tone	20	7.436	0.777	0.0171	0.0043	1	89.480	0.0571	1	89.480	869.7
981	wdc B wed 5 L u-hi f-on tone	20	6.783	0.352	0.0186	0.0045	1	84.842	0.0602	1	84.842	917.3
983	wdc B thu 6 L u-hi f-on tone	20	7.663	0.645	0.0166	0.0042	1	99.513	0.0513	1	99.513	782.0
987	wdc C thu 1 L u-hi f-on tone	20	7.413	0.782	0.0170	0.0044	1	83.720	0.0611	1	83.720	929.6
992	wdc D thu 2 L u-hi foff tone	20	4.477	0.036	0.0282	0.0066	1	81.245	0.0629	1	81.245	957.9
1000	wdc B thu 4 L u-hi f-on tone	20	7.498	0.787	0.0171	0.0044	1	83.750	0.0610	1	83.750	929.2
1004	wdc A thu 4 L u-hi f-on tone	20	7.831	0.856	0.0162	0.0042	1	97.010	0.0527	1	97.010	802.2
1007	wdc C thu 5 L u-hi f-on tone	20	8.700	1.691	0.0206	0.0065	1	85.647	0.0597	1	85.647	908.7
1010	den B tue 4 L u-hi f-on puls	20	7.235	0.778	0.0174	0.0045	1	83.749	0.0611	1	83.749	929.3
1015	den C wed 6 L u-hi f-on puls	20	8.125	0.798	0.0194	0.0070	1	83.808	0.0609	1	83.808	928.6
1019	den D wed 1 L u-hi foff puls	20	4.467	0.036	0.0282	0.0066	1	81.251	0.0629	1	81.251	957.8
1026	den A wed 2 L u-hi f-on puls	20	6.877	0.484	0.0183	0.0045	1	84.032	0.0608	1	84.032	926.1
1028	den B wed 3 L u-hi f-on puls	20	7.240	0.595	0.0174	0.0043	1	83.867	0.0609	1	83.867	927.9
1034	den C wed 4 L u-hi f-on puls	20	8.572	0.916	0.0212	0.0077	1	84.320	0.0607	1	84.320	923.0
1040	den D thu 6 L u-hi foff puls	20	4.473	0.037	0.0282	0.0066	1	81.253	0.0629	1	81.253	957.8
1046	den B thu 1 L u-hi f-on puls	20	7.113	0.665	0.0177	0.0045	1	83.682	0.0611	1	83.682	930.0
1049	den C thu 2 L u-hi f-on puls	20	8.236	0.812	0.0198	0.0073	1	83.941	0.0608	1	83.941	927.1
1059	den A thu 4 L u-hi f-on puls	20	6.735	0.484	0.0187	0.0046	1	83.687	0.0611	1	83.687	929.9
1065	den A thu 5 L u-hi f-on puls	20	6.802	0.466	0.0185	0.0045	1	84.211	0.0608	1	84.211	924.2
1067	den B fri 6 L u-hi f-on puls	20	7.254	0.770	0.0174	0.0045	1	83.678	0.0610	1	83.678	930.0
1071	den C fri 1 L u-hi f-on puls	20	10.311	1.449	0.0220	0.0064	1	86.524	0.0591	1	86.524	899.4
1078	den A fri 2 L u-hi f-on puls	20	6.804	0.446	0.0185	0.0045	1	84.052	0.0608	1	84.052	925.9
1080	den B fri 2 L u-hi f-on puls	20	7.240	0.723	0.0174	0.0044	1	83.834	0.0614	1	83.834	928.3

Table G-11. Test Results for Bit Transfer Failure Parameters: 512-Character Blocks

Test No.	Levels of Factors	Bit Error #	Bit Error Fail	Bit Error Pairs	Bit Error Failure Prob.	Bit Error Standard Deviation	Extra Bit #	Extra Bit Fail	Extra Bit Pairs	Extra Bit Failure Prob.	Extra Bit Standard Deviation	Bit Loss #	Bit Loss Fail	Bit Loss Pairs	Bit Loss Failure Prob.	Bit Loss Standard Deviation
680	ftw A mon 3 L u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
681	ftw B mon 3 L u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
698	ftw B tue 2 L u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
705	ftw C tue 3 L u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
709	ftw F tue 3 L u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
718	ftw A tue 4 L u-lo foff tone	77648	0	0	0.000	0.000	77648	0	0	0.000	0.000	81920	4272	4261	0.052	63.633
721	ftw B wed 2 L u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
722	ftw A wed 3 L u-lo foff tone	80480	0	0	0.000	0.000	80480	0	0	0.000	0.000	81920	1440	1431	0.018	37.612
727	ftw F wed 4 L u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
739	ftw F thu 1 L u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
743	ftw C thu 1 L u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
747	ftw A thu 2 L u-lo foff tone	80616	0	0	0.000	0.000	80616	0	0	0.000	0.000	81920	1304	1301	0.016	35.822
751	ftw B thu 3 L u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
759	ftw C thu 4 L u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
773	ftw A fri 1 L u-lo foff tone	81544	0	0	0.000	0.000	81544	0	0	0.000	0.000	81920	376	374	0.005	19.346
777	ftw B fri 2 L u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
787	sea B thu 1 L u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
797	sea F thu 3 L u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
805	sea B thu 4 L u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
808	sea A thu 5 L u-lo foff tone	81864	0	0	0.000	0.000	81864	0	0	0.000	0.000	81920	56	55	0.000	7.481
812	sea A fri 6 L u-lo foff tone	81824	0	0	0.000	0.000	81824	0	0	0.000	0.000	81920	96	95	0.001	9.792
816	sea F fri 1 L u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
821	sea A fri 2 L u-lo foff tone	81560	0	0	0.000	0.000	81560	0	0	0.000	0.000	81920	360	359	0.004	18.932
826	sea C mon 1 L u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
828	sea B mon 2 L u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
834	sea A mon 3 L u-lo foff tone	81568	0	0	0.000	0.000	81568	0	0	0.000	0.000	81920	352	350	0.004	18.721
837	sea F mon 4 L u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
849	sea B wed 5 L u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
851	sea B thu 6 L u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
857	sea A thu 1 L u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
859	sea F thu 2 L u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
865	sea B thu 3 L u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
874	sea A thu 4 L u-lo foff tone	80456	0	0	0.000	0.000	80456	0	0	0.000	0.000	81920	1464	1458	0.018	37.919
890	wdc C sun 5 L u-lo f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
892	wdc C mon 6 L u-lo f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
896	wdc F mon 1 L u-lo foff puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
901	wdc A mon 2 L u-lo foff puls	80944	0	0	0.000	0.000	80944	0	0	0.000	0.000	81920	976	968	0.012	31.054
905	wdc B mon 3 L u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
911	wdc C mon 4 L u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
914	wdc C mon 4 L u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
918	wdc C mon 5 L u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
920	wdc D tue 6 L u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
926	wdc A tue 1 L u-lo foff tone	80168	0	0	0.000	0.000	80168	0	0	0.000	0.000	81920	1752	1748	0.021	41.407
929	wdc B tue 2 L u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
934	wdc C tue 3 L u-lo f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
939	wdc D tue 4 L u-lo foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
951	wdc A tue 5 L u-hi f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
953	wdc A wed 6 L u-hi f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
960	wdc B wed 1 L u-hi f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
967	wdc C wed 2 L u-hi f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
970	wdc D wed 3 L u-hi foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
977	wdc A wed 4 L u-hi f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
981	wdc B wed 5 L u-hi f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
983	wdc B thu 6 L u-hi f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
987	wdc C thu 1 L u-hi f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
992	wdc D thu 2 L u-hi foff tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1000	wdc B thu 4 L u-hi f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1004	wdc A thu 4 L u-hi f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1007	wdc C thu 5 L u-hi f-on tone	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1010	den B tue 4 L u-hi f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1015	den C wed 6 L u-hi f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1019	den D wed 1 L u-hi foff puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1026	den A wed 2 L u-hi f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1028	den B wed 3 L u-hi f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1034	den C wed 4 L u-hi f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1040	den D thu 6 L u-hi foff puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1046	den B thu 1 L u-hi f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1049	den C thu 2 L u-hi f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1059	den A thu 4 L u-hi f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1065	den A thu 5 L u-hi f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1067	den B fri 6 L u-hi f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1071	den C fri 1 L u-hi f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1078	den A fri 2 L u-hi f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000
1080	den B fri 2 L u-hi f-on puls	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000	81920	0	0	0.000	0.000

Table G-12. Test Results for Block Transfer Failure and Availability Parameters: 512-Character Blocks

Test No.	Levels of Factors	Block Error					Extra Block				Block Loss					Transfer Denial				
		#	Fail	Pairs	Failure Prob.	Standard Deviation	#	Pairs	Failure Prob.	Standard Deviation	#	Fail	Pairs	Failure Prob.	Standard Deviation	#	Fail	Pairs	Failure Prob.	Standard Deviation
680	ftw A mon 3 L u-lo foff tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
681	ftw B mon 3 L u-lo f-on tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
698	ftw B tue 2 L u-lo f-on tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
705	ftw C tue 3 L u-lo foff tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
709	ftw F tue 3 L u-lo foff tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
718	ftw A tue 4 L u-lo foff tone	20	9	4	0.450	2.225	20	0	0.000	0.000	20	0	0	0.000	0.000	19	9	4	0.474	2.176
721	ftw B wed 2 L u-lo f-on tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
722	ftw A wed 3 L u-lo foff tone	20	7	1	0.350	2.133	20	0	0.000	0.000	20	0	0	0.000	0.000	19	6	0	0.316	2.026
727	ftw F wed 4 L u-lo foff tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
739	ftw F thu 1 L u-lo foff tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
743	ftw C thu 1 L u-lo foff tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
747	ftw A thu 2 L u-lo foff tone	20	2	0	0.100	1.342	20	0	0.000	0.000	20	0	0	0.000	0.000	19	2	0	0.105	1.338
751	ftw B thu 3 L u-lo f-on tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
759	ftw C thu 4 L u-lo foff tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
773	ftw A fri 1 L u-lo foff tone	20	2	1	0.100	1.342	20	0	0.000	0.000	20	0	0	0.000	0.000	19	2	1	0.105	1.338
777	ftw B fri 2 L u-lo f-on tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
787	sea B thu 1 L u-lo f-on tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
797	sea F thu 3 L u-lo foff tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
805	sea B thu 4 L u-lo f-on tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
808	sea A thu 5 L u-lo foff tone	20	1	0	0.050	0.975	20	0	0.000	0.000	20	0	0	0.000	0.000	19	1	0	0.053	0.973
812	sea A fri 6 L u-lo foff tone	20	1	0	0.050	0.975	20	0	0.000	0.000	20	0	0	0.000	0.000	19	1	0	0.053	0.973
816	sea F fri 1 L u-lo foff tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
821	sea A fri 2 L u-lo foff tone	20	1	0	0.050	0.975	20	0	0.000	0.000	20	0	0	0.000	0.000	19	1	0	0.053	0.973
826	sea C mon 1 L u-lo foff tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
828	sea B mon 2 L u-lo f-on tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
834	sea A mon 3 L u-lo foff tone	20	2	0	0.100	1.342	20	0	0.000	0.000	20	0	0	0.000	0.000	19	1	0	0.053	0.973
837	sea F mon 4 L u-lo foff tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
849	sea B wed 5 L u-lo f-on tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
851	sea B thu 6 L u-lo f-on tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
857	sea A thu 1 L u-lo foff tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
859	sea F thu 2 L u-lo foff tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
865	sea B thu 3 L u-lo f-on tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
874	sea A thu 4 L u-lo foff tone	20	6	1	0.300	2.049	20	0	0.000	0.000	20	0	0	0.000	0.000	19	5	1	0.263	1.919
890	wdc C sun 5 L u-lo f-on puls	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
892	wdc C mon 6 L u-lo f-on puls	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
896	wdc F mon 1 L u-lo foff puls	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
901	wdc A mon 2 L u-lo foff puls	20	8	2	0.400	2.191	20	0	0.000	0.000	20	0	0	0.000	0.000	19	3	1	0.158	1.589
905	wdc B mon 3 L u-lo f-on tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
911	wdc C mon 4 L u-lo f-on tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	1	0	0.053	0.973
914	wdc C mon 4 L u-lo f-on tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
918	wdc C mon 5 L u-lo f-on tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
920	wdc D tue 6 L u-lo foff tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
926	wdc A tue 1 L u-lo foff tone	20	4	2	0.200	1.789	20	0	0.000	0.000	20	0	0	0.000	0.000	19	4	2	0.211	1.777
929	wdc B tue 2 L u-lo f-on tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
934	wdc C tue 3 L u-lo f-on tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
939	wdc D tue 4 L u-lo foff tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
951	wdc A tue 5 L u-hi f-on tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
953	wdc A wed 6 L u-hi f-on tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
960	wdc B wed 1 L u-hi f-on tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
967	wdc C wed 2 L u-hi f-on tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
970	wdc D wed 3 L u-hi foff tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
977	wdc A wed 4 L u-hi f-on tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
981	wdc B wed 5 L u-hi f-on tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
983	wdc B thu 6 L u-hi f-on tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
987	wdc C thu 1 L u-hi f-on tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
992	wdc D thu 2 L u-hi foff tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
1000	wdc B thu 4 L u-hi f-on tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
1004	wdc A thu 4 L u-hi f-on tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
1007	wdc C thu 5 L u-hi f-on tone	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
1010	den B tue 4 L u-hi f-on puls	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
1015	den C wed 6 L u-hi f-on puls	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
1019	den D wed 1 L u-hi foff puls	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
1026	den A wed 2 L u-hi f-on puls	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
1028	den B wed 3 L u-hi f-on puls	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
1034	den C wed 4 L u-hi f-on puls	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
1040	den D thu 6 L u-hi foff puls	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
1046	den B thu 1 L u-hi f-on puls	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
1049	den C thu 2 L u-hi f-on puls	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
1059	den A thu 4 L u-hi f-on puls	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
1065	den A thu 5 L u-hi f-on puls	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
1067	den B fri 6 L u-hi f-on puls	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
1071	den C fri 1 L u-hi f-on puls	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
1078	den A fri 2 L u-hi f-on puls	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000
1080	den B fri 2 L u-hi f-on puls	20	0	0	0.000	0.000	20	0	0.000	0.000	20	0	0	0.000	0.000	19	0	0	0.000	0.000

APPENDIX H: ANALYSIS OF MULTIPLE TESTS

H.1 Latin Square and General Linear Model Analysis

H.1.1 Introduction

The experiment design described in Section 3 provided for separating and testing the main effects on each performance parameter of different network connections, city pairs (i.e., user pairs), days, and times of day. Main effects are first-order effects; that is, average effects disregarding possible second-order effects, or interactions, with other factors. In fact, in the analysis of variance referred to in Section 3, any second-order effects are combined with random variations to form the residual mean square with which each factor mean square is compared to test whether it is significant.

Other methods of testing for significant differences (modified chi-squared and F tests) have also been used, both of the same general type in that they make use of the variations among individual trials to judge whether mean differences among tests are significant. They have the disadvantage that the successive trials tend to be dependent in a way that is unknown and is modeled as Markov dependence, which is probably just an approximation to reality. Hence it is valuable to have another method such as the analysis of variance referred to previously.

Unfortunately, the analysis of variance also has a disadvantage: it is disrupted if there are missing test means, especially if the missing means include more than one of the 16 to be derived from each city. Some test means were in fact not obtained for almost all parameters in all cities, so that the Latin square design turned out not to be desirable. To be precise, 11 out of 176 possible Latin squares were complete, and an additional 11 had just one missing observation. (Randomized placement of tests within each city would have been better.) As a result, the analysis of variance, when it can be done at all, has to be done city by city, not with all cities together.

The complete Latin square analysis is illustrated in Section H.1.2 in one of the cases in which all 16 means were obtained. Analysis for the case of one missing mean is discussed in Section H.1.3. The alternative analysis, by the General Linear Model (GLM) procedure of the SAS computer software package (SAS Institute, Inc., 1985) is illustrated in Section H.1.4. The results are summarized in Section H.1.5.

H.1.2 Complete Latin Square Analysis

Data from one of the complete Latin squares consist of User Information Bit Transfer Rates in tests that transferred 512-character blocks from Washington to Boulder; these are shown in Table H-1. The analysis is easy and available in many books (e.g., Davies, 1956, Sec. 5.4).

The analysis uses the mean values for each day, each time of day, and each network connection listed along the margins of the table. It is evident that the biggest effect is the increase in transfer rate between Tuesday and Wednesday. It turns out that this is caused by a factor that was not considered in the design: the use of a low-utilization option (an additional 1-second delay between the input of successive blocks) on Monday and Tuesday and its removal during Wednesday and Thursday.

This conclusion is borne out by the formal analysis of variance shown in Table H-2. The second column contains the total sum of squares of deviations from the grand mean (867.50) and the component sums attributable to each source of variation. The total sum is

$$\sum_i \sum_j (Y_{ij(k)} - \overline{Y})^2 = \sum \sum Y_{ij(k)}{}^2 - (\sum \sum Y_{ij(k)})^2/16$$

$$= 124,900 - (1080)^2/16 = 52,000.0,$$

where $Y_{ij(k)}$ denotes the mean for the ith time of day, jth day, and (not independently) kth network and the calculations are made after subtracting 800 from each transfer rate. The sum of squares of deviations among days is

$$\sum_i \sum_j (Y_{\cdot j(\cdot)} - \overline{Y})^2 = \sum_j (\sum_i Y_{ij(k)})^2/4 - (\sum \sum Y_{ij(k)})^2/16$$

$$= 106,173.5 - 72,900.0 = 33,273.5,$$

where $Y_{\cdot j(\cdot)}$ denotes the day means. Similarly, the sums for times and networks are found, and the residuals sum is obtained by subtraction. Each F value in the last column is obtained by dividing the corresponding mean square by the residual mean square. It indicates a significant effect if it exceeds the

Table H-1. User Information Bit Transfer Rates (in bps) for for Tests Transmitting 512-Character Blocks from Washington on December 12-15, 1983

	M	Tu	W	Th	Means
0830	D 824	A 828*	B 926	C 930	877.00
1000	A 820*	B 820	C 929	D 958	881.75
1330	B 822	C 821	D 958	A 802	850.75
1500	C 822	D 821	A 870	B 929	860.50
Means	822.00	822.50	920.75	904.75	867.50
Network Means:	A 830.00	B 874.25	C 875.50	D 890.25	

*Later checking of data changed 820 and 828 to 793 and 802, respectively; because significance conclusions were not affected, the calculations in this appendix have not been changed.

Table H-2. Analysis of Variance Table for User Information Bit Transfer Rates in Table H-1

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F
Times	2,491.5	3	830.50	0.62
Days	33,273.5	3	11,091.17	8.21
Networks	8,133.5	3	2,711.17	2.01
Residuals	8,101.5	6	1,350.25	
Total	52,000.0	15		

$F_{3,6,0.05} = 4.76$

tabulated F distribution percentage point, $F_{3,6,0.05} = 4.76$. In this case only the day effect is significant, and that evidently arises from the change in the utilization option.

There were ten other Latin squares with no missing observations, all of them arising from the same set of tests that transmitted 512-character blocks from Washington, DC. Three of these comprise the measured values of Block Transfer Time, User Fraction of Block Transfer Time, and User Fraction of Input-Output Time. These were also analyzed as above, with significance results summarized in Table H-3. Block Transfer Time varied significantly only among network connections. There were no significant differences in User Fraction of Block Transfer Time due to any of the three factors (time of day, day of week, or network), even with the change from low to high utilization midweek and one value of 0.0000; the mean value was 0.0170. On the other hand, the User Fraction of Input-Output Time was greatly affected by the change from low to high utilization, averaging 0.2272 and 0.0600 in the two respective cases. Time of day again had no effect. Network connections differed rather little in this user fraction on the average; calculated values were 0.139 for PDN A connections and 0.144 or 0.145 for the others. Surprisingly, these differences were enough to test statistically significant at the 5% level.

The other seven complete Latin squares were obtained with the various types of failure probability and were so uniform that the above standard analysis was unnecessary. Four of the seven types of failure did not occur at all in the 16 tests: bit error, extra bit, block loss, and extra block. The other three types of failure--bit loss, block loss, and transfer denial--occur in only two tests, both on PDN A connections, with mean estimated probabilities of 0.017, 0.300, and 0.184 respectively, which (by a standard error test) differ significantly from zero, the value in all 14 other tests. The results are briefly summarized in Table H-3.

H.1.3 Latin Square Analysis With One Missing Observation

Latin squares with just one missing observation can be analyzed fairly readily by modification of the above complete Latin square analysis (Johnson and Leone, 1977, p. 678). The missing observation is replaced by a least-squares estimate based on the other 15 observations (in this case of a 4x4 square), the sums of squares are calculated as before, and the three-factor sums of squares are reduced by differing amounts according to the formula given

Table H-3. Significant Effects in Analyses of All Complete Latin Squares and Latin Squares With Just One Missing Observation (All from Washington, DC)

Low utilization Monday and Tuesday, high utilization Wednesday and Thursday.
There were 16 tests on 512-character blocks, 15 on 64-character blocks.
Factors having a significant effect on a parameter at the 5% significance level are marked X.

	Time of Day		Day of Week		Network	
Parameter	64	512	64	512	64	512
Bit Transfer Rate			X	X	X	
Block Transfer Time						X
User Fraction of Block Transfer Time			X		X	
User Fraction of Input-Output Time			X	X		X
Bit Error Probability						
Bit Loss Probability			*	**		
Extra Bit Probability						
Block Error Probability			*	**		
Block Loss Probability			*			
Extra Block Probability						
Transfer Denial Probability				**		

*One test only (PDN A 0830 Tuesday) with probability estimate significantly different from zero but not assignable to any particular one of the three factors.

**Two tests only (PDN A 0830 Tuesday and 1000 Monday) with probability estimates different from zero, both significantly so, assuming independence (except transfer denial Monday), but not assignable to any particular one of the three factors.

by Johnson and Leone (op. cit., p. 678). After these reductions the residual sum of squares is again obtained by subtraction, but now has 5 degrees of freedom rather than 6, because of the missing observation. The rest of the analysis is the same as for a complete Latin square.

There were 11 Latin squares with just one missing observation, all obtained with 15 tests from Washington, DC, transferring 64-character blocks. As with the 512-character blocks, these tests were not conducted as designed because another factor, utilization, was changed between Tuesday and Wednesday. This very significantly affected the user information bit transfer rate and the user fractions of block transfer time and input-output time, the rate changing on the average from 505 bps with low utilization to 897 bps with high utilization, the former fraction from 0.0649 to 0.2025, and the latter fraction from 0.99 to 0.47. On the other hand, the block transfer times themselves were not significantly affected by the change in utilization.

Four of the seven Latin squares for failure probability parameters with 64-character blocks had no failures in any of the 15 tests: bit error, extra bit, extra block, and transfer denial. The other three parameters--bit loss, block error, and block loss--experienced failure only in one test, over PDN A at 0830 Tuesday; however, their estimated values (0.097, 0.038, and 0.31, respectively) are significantly different from zero by a standard error calculation.

The significance results from all of the Latin squares for tests using 64-character blocks are summarized in Table H-3 along with those for tests using 512-character blocks.

H.1.4 Latin Square Analysis With Several Missing Observations

Latin squares with more than one missing observation can be analyzed with some difficulty by modifying the above complete Latin square analysis in certain other special cases, but it is desirable, as well as necessary in most cases, to analyze them by a General Linear Model procedure such as provided by SAS Institute Inc. (1985). These procedures are not unique, and it is difficult to determine which, if any, are applicable to a particular set of data (Speed, Hocking, and Hackney, 1978; Hocking, Speed, and Coleman, 1980). We have applied two of the four SAS Types I-IV to three incomplete Latin squares.

The first incomplete Latin square considered is simply the complete square of Table H-1 with the transfer rate of 929 bps for a Network C connection on Wednesday arbitrarily deleted. The purpose in analyzing it is to become acquainted with and check the various types of analyses and their relative results. One analysis is the standard method used in Section H.1.3.

Another is the SAS Type III, the results of which are given in Table H-4; they are identical with the results of the standard method. The sums of squares do not now add to the original total because each sum except the residual sum is reduced by an amount attributable to sources other than the source under consideration. The SAS Type I analysis was also performed, with closely similar results: probabilities of exceeding the calculated F values under the hypothesis of no real effects were 0.610, 0.036, and 0.274 respectively. Both of these analyses thus confirm the results of the complete Latin square analysis--significant day effect, nonsignificant time-of-day and network effects--despite deleting one observation.

Mean values of Block Transfer Time from a Latin square set of tests from Seattle using medium-length (128-character) blocks are shown in Table H-5. One test gave no data, and Friday afternoon no tests were even started. Furthermore, two other tests could not be performed as scheduled at 1500 because the networks could not be accessed, so other networks were substituted. This resulted in two tests using PDN B on Thursday, December 1, and two using PDN A on Thursday, December 8. (The Seattle tests could not be started on Monday, November 28, because the air freight carrier took five days to deliver the computer from Denver). All of the tests of Table H-5 were conducted with low utilization, unlike those of Table H-1.

The results of the SAS Type III analysis of the data in Table H-5 are shown in Table H-6. There are no significant differences among days or times of day, but there is a highly significant difference among networks. The latter confirms the obvious consistently much faster transfer using Network F (FTS) connections. With only 3 degrees of freedom for error (the residuals being assumed to measure random error only) there is substantial chance of failing to detect real sources of variation from days or times, but obviously this did not happen to variation among networks. The SAS Type I analysis was also performed for these data, with results closely similar to the Type III results; the respective probabilities of exceeding the observed values of F

Table H-4. Type III General Linear Model Procedure for User Information Bit Transfer Rates in Table H-1 with the Value for 1000 W Deleted

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F	Probability > F
Times	3,014.1	3	1,004.7	0.66	0.610
Days	31,057.4	3	10,352.5	6.83	0.032
Networks	8,592.2	3	2,864.1	1.89	0.249
Residuals	7,578.8	5	1,515.8		
Corrected Total	52,000.0	14			

$F_{3,5,0.95} = 5.41$

Table H-5. Mean Block Transfer Times (in seconds) for Tests Transmitting 128-Character Blocks from Seattle on December 1-8, 1983

	Th 12/1	F 12/2	M 12/5	Th 12/8	Means
0900	B 2.814	F 1.119	C 2.802	A 3.075	2.452
1030	C -----	A 2.750	B 2.780	F 1.122	2.217
1330	F 1.121	C -----	A 2.752	B 2.808	2.227
1500	B 2.751	-----	F 1.120	A 2.889	2.253
Means	2.229	1.934	2.364	2.474	2.300
Network Means:	A 2.866	B 2.788	C 2.802	F 1.120	

Table H-6. Type III General Linear Model Procedure for Block Transfer Times in Table H-5

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F	Probability > F
Times	0.04816068	3	0.016054	5.21	0.104
Days	0.03241346	3	0.010804	3.51	0.165
Networks	7.50675183	3	2.502251	812.86	0.0001
Residuals	0.00923504	3	0.003078		
Corrected Total	7.59656101	12			

$F_{3,3,0.95} = 9.28$

under the hypothesis of no real effects were 0.104, 0.190, and 0.0001 respectively.

One other set of test results, medium-length block transfer times from Washington, DC, on December 11-15, 1983, were analyzed using the SAS General Linear Model procedure. Two of the scheduled 16 tests failed to yield data. The detailed results are not given here because the utilization level changed on Wednesday as for the tests in Table H-1 and the results are somewhat, though not entirely, similar to the previous results. The probabilities of exceeding the observed values of F are as follows:

	Type III Analysis	Type I Analysis
Times	0.360	0.360
Days	0.051	0.037
Networks	0.012	0.011

The networks differ significantly because transfer via the Public Switched Telephone Network was much faster than transfer via any of the PDNs. The days differ marginally significantly because of the change from low to high utilization on Wednesday and Thursday. Time of day again made no difference.

H.1.5 Summary and Conclusions

Twenty-four out of the total of 176 planned 4x4 Latin square sets of tests were analyzed, 22 of them by standard methods and three (one of them also done by the standard method) by the SAS Institute program for the General Linear Model. The analysis indicates whether there are statistically significant effects assignable to network connections, days of the week, or times of day. The results are summarized in Tables H-3 and H-6 and in the last paragraph of Section H.1.4. The remaining 152 Latin squares had enough missing observations that formal analysis was not considered worth attempting.

All but one of the analyses were performed on data obtained during a week of testing in Washington, DC, in which utilization was changed from low to high beginning Wednesday. In most cases the factor "day of the week" showed a significant effect, probably as a result of the change in utilization. In the one analysis without such change, day of the week did not have a significant effect (Table H-6). In no case did time of day show a significant effect by itself, though the analyses on the failure probabilities did not isolate particular factors; see the footnotes to Table H-3. Network connections differed significantly in some cases, especially, as expected, for those using a switched telephone network.

We conclude that the Latin square type of design, so attractive in prospect, is not in retrospect the best type of design for this area of data network performance testing because of the substantial chance of one or more tests per week not being achievable at the scheduled time. A better design would be to schedule equal numbers of tests on each network but randomize the incidence of each chronologically over the times of day and days of the week. Failure of one or more tests would not jeopardize the analysis; i.e., unequal numbers do not affect the analysis appreciably. Furthermore, a failed test could be replaced by a test conducted later.

The randomized block design (the block being the city pair) would not permit separating out variations among times of day from variations among days, but the above analyses show no significant effect of time of day and the significant effect of changing days can be attributed to changing utilization. Hence we have some justification for lumping variations among <u>tests</u>, whether they occur on different days or different times of day, into one category. That is just what is done in the next section in calculating overall confidence limits for performance parameter estimates that characterize a given network connection.

The analyses referred to in Section H.1.1, which use the variations among trials within tests to judge variations among tests, show in most cases that there are significant variations among tests, so usually we cannot just pool trials from different tests to obtain confidence limits; hence the need for the procedures described in Sections H.2 and H.3.

H.2 Procedure for Calculating Overall Time Parameter Confidence Limits

H.2.1 Introduction - The General Idea

The specific purpose of this section is to provide formulas for calculating confidence intervals for estimates of time parameters, such as Access Time, that characterize network connections tested by ITS in 1983, but they can be applied more generally. It is assumed that there are three sources of variation: among city pairs, among tests within city pairs, and among trials within tests. Furthermore, it is assumed that they add up linearly:

Individual time measurement

$$\begin{aligned} = \text{ true value } &+ \text{ deviation for a particular city pair} \\ &+ \text{ deviation for a particular test} \\ &+ \text{ deviation for a particular trial,} \end{aligned} \quad (1)$$

or, in symbols,

$$y_{ijk} = \mu + a_i + b_{ij} + e_{ijk} \; , \quad \begin{aligned} i &= 1, 2, \ldots, p; \\ j &= 1, 2, \ldots, m_i; \\ k &= 1, 2, \ldots, n_{ij}. \end{aligned} \quad (2)$$

It is also assumed that the p city pairs have been picked at random from all possible pairs of interest served by a given network, that for each city pair the tests actually conducted are a random sample of possible tests of interest using the network, and that either the n_{ij} trials in a test are independent or any correlation is taken into account in calculating the standard error of the mean of each test,

$$y_{ij\cdot} = \frac{1}{n_{ij}} \sum_{k=1}^{n_{ij}} y_{ijk} \; . \quad (3)$$

The STAT analysis computer program (Miles, 1984, Sections A.2 and A.3) does take such account in calculating the confidence limits for the mean time from individual tests. This program also provides for pooling the results from tests the means of which do not differ significantly (as shown by a modified F test). If all tests from all cities using a particular network connection can thus be pooled, the program provides confidence limits for the estimate of the time parameter that characterizes the network connection. It is suggested that these confidence limits from pooling all trial results be calculated for comparison even if the test means do differ significantly; the STAR program described in Section 4.3 of this report has been modified to do that.

One may rationalize the above pooling method by claiming that the among-test and among-city components of variance may be small even if the means differ statistically significantly and hence the resulting confidence limits are good approximations. This rationalization may not be justified, but such limits are of sufficient interest to calculate for comparison with limits based on more complete models.

Even though test means have been found to differ significantly, it may be that city-pair means do not differ significantly, and this can be tested by an F test against the variance among test means within city pairs. If city-pair means do not differ significantly, all test means (but not individual trials) can be pooled to obtain confidence limits for a parameter estimate characterizing the particular network connection. On the other hand, if the above F test shows significant differences among city pairs, then one must calculate confidence limits based on those differences.

The third assumption above is not satisfied in the ITS experiment, but it is desirable to show how confidence limits could be applied if it were satisfied. The limits may be quite realistic even though the assumption is not satisfied. In fact, the limits tend to be quite far apart because there are so few city pairs in the experiment, and a future experiment with the object of characterizing a network connection overall should very probably involve more city pairs despite the cost. (A quantitative theory has been developed that confirms this intuitive result, similar to that in Appendix A of NTIA Report 79-21 (Crow, 1979)). In addition, the n_{ij} and m_i should be the same for all i and j, but moderate variations impose little error.

A fourth assumption (implicit in the pooling method but not stated above) is that the (population) variances of a_i, b_{ij}, and e_{ijk} and the covariance of e_{ijk} and $e_{ijk'}$ are constant throughout, i.e., independent of i, j, and k. The variances are denoted by σ_a^2, σ_b^2, and σ_e^2.

A fifth assumption, which is not critical, is that the a_i, b_{ij}, and e_{ijk} are normally (Gaussian) distributed. It is not critical because the confidence limits are approximately correct without the assumption.

The complete model is outlined in the first paragraph above. Section H.2.2 outlines the justification for pooling all trials and the resulting confidence limits. Section H.2.3 presents the test for differences among city-pair means and the confidence limits resulting when differences among city-pair means are not significant. Finally Section H.2.4 presents the confidence limits based on differences among city-pair means, which tend to be wider than the others. Numerical examples of the Access Time measurements are given in all three cases. The general procedure and the three methods are summarized in Section H.2.5.

H.2.2 Limits Based on Pooling All Trials: $\sigma_a = \sigma_b = 0$

It is desirable to calculate overall confidence limits for a parameter estimate characterizing a network connection by pooling trials from all tests in all cities if such pooling is justified, because this yields by far the most degrees of freedom, the Student t coefficient is smallest, and the confidence interval tends to be shortest (of the three intervals under consideration). The pooling is justified if a modified F test incorporated in the STAR program shows no significant difference among the means of all tests.

Approximate 100(1-2α)% confidence limits for the performance parameter μ are then given by

$$\bar{y} \pm t_{N'-1,\, \alpha}\, s_{\bar{y}} \quad , \tag{4}$$

where

$$\bar{y} = \frac{1}{N} \sum_{i=1}^{p} \sum_{j=1}^{m_i} \sum_{k=1}^{n_{ij}} y_{ijk} = \frac{1}{N} \sum_{i=1}^{p} \sum_{j=1}^{m_i} n_{ij}\, y_{ij\cdot} \quad , \tag{5}$$

$$N = \sum_{i=1}^{p} \sum_{j=1}^{m_i} n_{ij} \quad , \quad N' = N \, \frac{1 - \bar{r}_1}{1 + \bar{r}_i} \quad , \tag{6}$$

$$s_{\bar{y}}^2 = \frac{s^2}{N} \, \frac{1 + \bar{r}_1}{1 - \bar{r}_i} \quad , \tag{7}$$

$$s^2 = \frac{1}{N-1} \sum_{i=1}^{p} \sum_{j=1}^{m_i} \sum_{k=1}^{n_{ij}} (y_{ijk} - \bar{y})^2 \quad , \tag{8}$$

$$\bar{r}_1 = \frac{1}{s^2(N-1)} \sum_{i=1}^{p} \sum_{j=1}^{m_i} \sum_{k=1}^{n_{ij}} (y_{ijk} - \bar{y})\,(y_{ij,k+1} - \bar{y}) \tag{9}$$

($y_{ij,n_{ij}+1} = y_{i,j+1,1}$, etc., in the latter), and $t_{N'-1,\alpha}$ is the upper Student t 100α percentage point with N'-1 degrees of freedom (d.f.). These formulas appear more formidable than they actually are; they merely describe the pooling together of all test trials into one chronological sample. Thus they comprise the same formulas used for producing confidence limits for an individual test.

Example. We consider access times in tests using PDN A connections in Seattle, WA, Washington, DC, and Fort Worth, TX. There were 11 different tests with $n_{ij} = 15$ to $n_{ij} = 20$ successful access attempts in each (all used tone dialing). A modified F test showed significant differences among the test mean values, but for comparative illustration we compute the confidence limits obtained by pooling all 209 access times into one sample. From the computer program, we find approximate 95% confidence limits,

$$41.732 \pm 0.597 = 41.7 \pm 0.6 \text{ seconds}$$

or 41.1 and 42.3 seconds. (The program uses N - 1 d.f. to obtain the Student t coefficient rather than N' - 1, but the effect is negligible because $\bar{r}_1 = 0.4998$, so that N = 209, N' =70, $t_{N-1,0.025} = 1.972$, $t_{N'-1,0.025} = 1.994$.)

H.2.3 Limits Based on Variance Among Tests: $\sigma_a = 0$, $\sigma_b \neq 0$

We first test whether the city-pair mean access times differ significantly based on the differences among test mean access times within city pairs, using a standard F test:

$$F_{p-1,\, M-p} = \frac{\sum_{i=1}^{p} m_i \, (y'_{i\cdot\cdot} - \bar{y}')^2 \,/\, (p-1)}{\sum_{i=1}^{p} \sum_{i=1}^{m_i} (y_{ij\cdot} - y'_{i\cdot\cdot})^2 \,/\, (M-p)} \tag{10}$$

$$M = \sum_{i=1}^{p} m_i \quad , \quad y'_{i\cdot\cdot} = \frac{1}{m_i} \sum_{j=1}^{m_i} y_{ij\cdot} \, , \tag{11}$$

$$\bar{y}' = \frac{1}{M} \sum_{i=1}^{p} \sum_{j=1}^{m_i} y_{ij\cdot} = \frac{1}{M} \sum_{i=1}^{p} m_i y'_{i\cdot\cdot} \quad . \tag{12}$$

If $F_{p-1,M-p}$ exceeds the tabulated percentage point $F_{p-1,M-p,\alpha}$, then the hypothesis that the city-pair means are equal is rejected. Otherwise the hypothesis is accepted, and we are justified in calculating confidence limits for μ from a pooled estimate of variance among tests. The $100(1-2\alpha)\%$ confidence limits for μ are

$$\bar{y}' \pm t_{M-1,\alpha} \, s_{\bar{y}'} \tag{13}$$

where

$$s_{\bar{y}'}^2 = \frac{1}{M(M-1)} \sum_{i=1}^{p} \sum_{j=1}^{m_i} (y_{ij\cdot} - \bar{y}')^2 \quad . \tag{14}$$

<u>Example</u>. We continue the preceding example and list all of the individual test means:

Seattle:	Test 811	$y_{11\cdot} = 41.163$	Washington, DC:	Test 928	$y_{21\cdot} = 44.500$		
	815	$y_{12\cdot} = 41.576$		952	$y_{22\cdot} = 39.813$		
	823	$y_{13\cdot} = 42.439$		978	$y_{23\cdot} = 42.304$		
	835	$y_{14\cdot} = 42.954$		997	$y_{24\cdot} = 41.751$		
	858	$y_{15\cdot} = 42.284$					
	876	$y_{16\cdot} = 42.313$	Ft. Worth:	Test 775	$y_{31\cdot} = 38.291$		
		$y_{1\cdot\cdot} = 42.1215$	$y_{2\cdot\cdot} = 42.092$		$y_{3\cdot\cdot} = 39.291$		
$M = 11$		$\bar{y}' = 41.762545$					

$$F_{2,8} = \frac{13.2588793/2}{13.2267635/8} = \frac{6.629}{1.653} = 4.01$$

Since $F_{2,8,0.05} = 4.46$, the city means do not differ significantly, and we are justified in using (13):

$$s_{\bar{y}'}^2 = (13.2588793 + 13.2267635)/(10 \times 11) = 0.24078.$$

95% confidence limits for μ are

$$41.763 \pm 2.228 \times 0.49069 = 41.8 \pm 1.1$$

or 40.7 and 42.9 seconds. These are wider than those in the previous section, mostly because of the significant variation between test means but somewhat because of the fewer d.f., 10 rather than 208. We note that $\bar{y}'$ differs slightly from $\bar{y} = 41.732$; they are equal in general only if the n_{ij} are all equal.

H.2.4 Limits Based on Variance Among City Pairs: $\sigma_a \neq 0$

If the city-pair means are found to differ significantly by the F test at the beginning of Section H.2.3, then we are forced to use $100(1-2\alpha)\%$ confidence limits based on the variance among city pairs:

$$\bar{y}'' \pm t_{p-1,\alpha}\, s_{\bar{y}''} \qquad (15)$$

where

$$\bar{y}'' = \frac{1}{p} \sum_{i=1}^{p} y'_{i\cdot\cdot} \quad , \qquad (16)$$

$$s_{\bar{y}''}^{\,2} = \frac{1}{p(p-1)} \sum_{i=1}^{p} (y'_{i\cdot\cdot} - \bar{y}'')^2 \quad . \qquad (17)$$

It is worth noting the range of values of the Student t percentage point for 95% confidence limits:

p	p-1	$t_{p-1,0.025}$
2	1	12.706
3	2	4.303
4	3	3.182
5	4	2.776
10	9	2.262
∞	∞	1.960

Aside from the question of costs, the rapid initial decrease of $t_{p-1,0.025}$ shows that it is desirable to measure at least four city pairs. In addition, the standard error of $\bar{y}''$, $s_{\bar{y}''}$, decreases in proportion to $p^{-1/2}$, so increasing p increases precision in two ways.

Example. We continue the example of access times using PDN A connections, although in this case we have seen that the city-pair means do not differ significantly; we will thus prefer the already calculated limits based on the variance among test means. For comparison we calculate $\bar{y}'' = 40.835$, $s_{\bar{y}''} = 1.272$, so the 95% confidence limits for μ are

$$40.835 \pm 4.303 \times 1.272 = 40.8 \pm 5.5$$

or 35.3 and 46.3 seconds.

H.2.5 Summary

We compare the numerical results from the three methods for calculating confidence limits for estimates of Access Time using PDN A connections:

Method	d.f., f	$t_{f,0.025}$	Standard Error	95% Limits
Among trials	208	1.972	0.181	41.7 ± 0.6
Among tests	10	2.228	0.491	41.8 ± 1.1
Among cities	2	4.303	1.272	40.8 ± 5.5

The proper choice of limits in this example was shown in Section H.2.3 to be that based on variance among tests, since the test means differ significantly but the city-pair means do not. The precision from among tests is five times that from among city pairs, of which a factor of 2.5 is due to the standard error of the mean and a factor of 2 to the t coefficient.

Since there may well be significant differences among city pairs in general, the number of city pairs should be made as large as the budget and time permit.

In summary, then, the procedure for calculating confidence limits for a time performance parameter is:

(i) Determine by the modified F test in the computer program whether the means from all tests in all cities differ significantly;

(ii) if not, calculate limits based on variance among all trials, expression (4);

(iii) if so, determine whether city-pair means differ significantly using (10);

(iv) if not, calculate limits based on variance among test means, expression (13);

(v) if so, calculate limits based on variance among city-pair means, expression (15).

H.3 Procedure for Calculating Overall Failure Probability Confidence Limits

H.3.1 Introduction

The purpose of this section is to provide formulas for calculating confidence intervals for estimates of failure probability parameters, such as Access Denial Probability, that characterize network connections tested by ITS in 1983, but they can be applied more generally. The procedure is much the same as that for time parameters described in Section H.2 but differs because the observations are just 0 or 1 (failure or success) and because the test means (failure ratios) vary asymmetrically about the population parameter value and cannot be assumed to follow a normal distribution even approximately. They can, however, be transformed to approximate normality by

$$y_{ij} = \frac{1}{2}\left[\sin^{-1}\left(\frac{s_{ij}}{n_{ij}+1}\right)^{1/2} + \sin^{-1}\left(\frac{s_{ij}+1}{n_{ij}+1}\right)^{1/2}\right]\frac{180}{\pi}\text{ degrees} \qquad (18)$$

(Bishop et al., 1975, p. 367, eq. (10.7-6)), where s_{ij} is the number of failures and n_{ij} is the number of trials in the jth test of the ith city pair, $j = 1, 2, \ldots, m_i$ and $i = 1, 2, \ldots, h$, h being used here instead of p because p is used here for probability estimates: $p_{ij} = s_{ij}/n_{ij}$.

If P denotes the (population) performance parameter and the occurrences of failures on different trials are independent, then y_{ij} has an asymptotic normal distribution with mean $\sin^{-1}\sqrt{P}$ and variance $(4n_{ij})^{-1}$ (Bishop et al., op. cit., p. 367). When there is dependence, it is assumed here that this still holds except that the variance is multiplied by a constant (which is a function of the autocorrelations among trials but need not be evaluated, it turns out).

The most simply described procedure would be to transform all the data by (18) and proceed as in Section H.4. However, it seems better to refrain from transformation if the probability estimates p_{ij} do not differ significantly. Often the present estimates do not differ significantly, partly because of small sample sizes.

Referring to Section H.2.2, we can conveniently indicate a conclusion of no significant difference overall as $\sigma_a = \sigma_b = 0$, i.e., no variance among city pairs and no variance among tests within city pairs, but the differences will be tested by chi-squared tests, as detailed in the next subsection, H.3.2.

H.3.2 Limits Based on Pooling All Trials: $\sigma_a = \sigma_b = 0$

It may be possible to accept the hypothesis that all test probabilities are equal based on the assumption of independence; then a fortiori the hypothesis would also be accepted based on an assumption of positive dependence. (This step is not necessary but seems worthwhile because of the simplification; one can go directly to the test based on dependence as in (A-62) of Miles (1984).) The test is

$$X^2_{M-1} = \sum_{k=1}^{M} \frac{n_k(p_k - \bar{p})^2}{\bar{p}(1 - \bar{p})} \tag{19}$$

$$= \frac{n}{\bar{p}(1 - \bar{p})} \sum_{k=1}^{M} (\bar{p}_k - \bar{p})^2 \quad \text{if all } n_k = n \quad ,$$

where $p_k = s_k/n_k$, $\bar{p} = \sum s_k/\sum n_k$, and there are n_k runs over all $M = \sum m_i$ tests in all cites. If the calculated X^2_{M-1} does not exceed the tabulated chi-squared percentage point $X^2_{M-1,\alpha}$, the hypothesis is accepted, and confidence limits for P are calculated using the pooled data and the formulas on pp. 68-72 of Miles (op. cit.).

On the other hand, if the above test calls for rejection, then the hypothesis is further tested taking account of dependence as on pp. 74-75 of Miles (op. cit.). It is assumed that the dependence factors in different tests do not differ significantly; this can be tested as in (A-58) of Miles (op. cit.), but no provision for significantly different factors is made here because it is unlikely that significant difference can be found and the error in confidence limits resulting from assuming equality seems negligible. If the hypothesis of equal P_k is now accepted, the confidence limits for P can be calculated from the pooled data as above. If the hypothesis is still rejected, then the data should not be pooled, and the procedure continues as in Section H.2.3.

Example 1. We consider access failures of all kinds in tests using PDN A connections in Seattle, WA; Washington, DC; and Fort Worth, TX. There were 11 tests with 20 access attempts each, so $n_{ij} = n = 20$. In Seattle, $m_1 = 6$ and $p_{ij} = 0$ except for $p_{11} = 1/20 = 0.05$ and $p_{14} = 5/20 = 0.25$. In Washington, DC, $m_2 = 4$, $p_{21} = p_{22} = 0$, $p_{23} = 2/20 = 0.10$, and $p_{24} = 3/20 = 0.15$. In Fort Worth, $m_3 = 1$ and $p_{31} = 0$. Hence $\overline{p} = 11/220 = 1/20 = 0.05$.

Test for significance of differences of p_{ij} based on independence:

$$X^2_{11-1} = \frac{20}{0.05 \times 0.95} \sum_{i,j} (p_{ij} - 0.05)^2 = 29.47,$$

$$X^2_{10,0.05} = 18.31, \quad X^2_{10,0.005} = 25.19.$$

Hence the p_{ij} differ significantly, at least based on the assumption of independence among access attempts.

Test for significance of differences of p_{ij} based on dependence: In 7 tests with $s_{ij} = 0$, the conditional probability λ (P_{11} in Miles (op. cit.)) is indeterminate. In 3 tests with $s_{ij} = 1$, 2, or 3, the number of pairs of successive failures $r_{ij} = 0$, so $\hat{\lambda} = 0$. In one test, $s_{ij} = 5$, $r_{ij} = 4$, so $\hat{\lambda} = 4/(5 - 0.25) = 0.84211$. Hence

$$\hat{\lambda}_{ave} = 4/(11 - 11 \times 0.05) = 0.38278,$$

$$\hat{\rho} = (\hat{\lambda}_{ave} - \overline{p})/\overline{q} = 0.35029,$$

$$\hat{\sigma}^2_{p_{ij}} = (0.05 \times .95/20)\ 1.99531 = 0.0047389,$$

$$\chi^2_{10} = 14.77.$$

Hence, the p_{ij} are not significantly different after all, and the data can be pooled. The mean estimate of P is $\sum s_{ij} / \sum n_{ij} = 0.05$. The 95% normal approximation confidence limits from (A-36) with $n = 220$, $s = 11$, $u_{0.025} = 1.960$ are $P_{UN} = 0.13494 = 0.135$ and $P_{LN} = 0.00083 = 0.0008$. The 95% modified Poisson approximation confidence limits from (A-41) are $P_{UP} = 0.1044 = 0.104$ and $P_{LP} = 0.0144$. The average limits (A-31) are $P_U = 0.12$ and $P_L = 0.01$. (Alternative, probably better, quadratic modified Poisson limits are 0.1128 and 0.0195, which lead to average limits of 0.12 and 0.01 also.)

H.3.3 Limits Based on Variance Among Tests: $\sigma_a = 0$, $\sigma_b \neq 0$

If the data cannot be pooled as above, then they are transformed by (18) and treated just like time data as in Sections H.2.3 and H.2.4. The resulting mean estimate and confidence limits apply to the mean of the Y_{ij}, $\sin^{-1}\sqrt{P}$ and need to be inverted to apply to P. For example, the lower limit for y, μ_L, yields the lower limit for P via

$$P_L = \sin^2 \mu_L \quad . \tag{20}$$

No further theory is needed, and we proceed with the data of Example 1 above, assuming for illustration that the p_{ij} do differ significantly (contrary to the fact found above).

<u>Example 2</u>. From Example 1 and equation (18):

$p_{11} = 1/20$: $y_{11} = 15.2898$. $p_{14} = 5/20$: $y_{14} = 30.7587$.

$p_{ij} = 0/20$: $y_{ij} = 6.3022$, $j = 2, 3, 5, 6$.

$m_1 = 6$, $y_{1.} = 11.8762$.

$p_{21} = p_{22} = 0/20$: $y_{21} = y_{22} = 6.3022$.

$p_{23} = 2/20$: $y_{23} = 20.0915$. $p_{24} = 3/20$: $y_{24} = 24.0422$.

$m_2 = 4$, $y_{2.} = 14.1845$.

$p_{31} = 0/20$: $y_{31} = 6.3022 = y_{3.}$, $m_3 = 1$.

F test of city-pair means: $\bar{y}' = 134.2976/11 = 12.20887$,

$$F_{2,8} = \frac{25.5826}{93.6009} = 0.273.$$

Since $F_{2,8} < 1$, the city-pair means do not differ significantly, and confidence limits based on the variance among all tests are justified. From (14), $s_{\bar{y}}' = 2.6968$.

Approximate 95% confidence limits for $\sin^{-1}\sqrt{P}$

$= 12.209 \pm 2.228 \times 2.6968 = 12.209 \pm 6.008$

or 6.201 and 18.217 degrees. From (20):

Approximate 95% confidence limits for P

$= 0.0117$ and 0.0977, or $(0.01, 0.10)$.

Estimate of P: $P = \sin^2 12.209 = 0.0447 \doteq 0.04$.

Alternative estimate of P:

$$P = \frac{1}{11} \sum_{i=1}^{3} \sum_{j=1}^{m_i} p_{ij} = 0.05,$$

which is the same as the estimate in Example 1 in this case because all n_{ij} are equal.

H.3.4 Limits Based on Variance Among Cities: $\sigma_a \neq 0$

We proceed for illustration to assume (contrary to the findings in both Example 1 and Example 2) that there are significant differences among city-pair access failure probabilities, so that confidence limits for P must be based on (15).

Example 3. From (16), $\bar{y}'' = 32.3629/3 = 10.7876$.

From (17), $s_{\bar{y}''} = 2.3396$.

Approximate 95% confidence limits for $\sin^{-1}\sqrt{P}$:

$10.7876 \pm 4.303 \times 2.3396 = 10.788 \pm 10.067$

or 0.721 and 20.855 degrees.

Approximate 95% confidence limits for P:

0.000158 and 0.1267 (or 0.0002 and 0.13).

Estimate of P: $P = \sin^2 10.7876 = 0.03503 \doteq 0.04$.

Alternative estimate of P:

$$P = \frac{1}{3}(p_{1.} + p_{2.} + p_{3.})$$

$$= \frac{1}{3}\left(\frac{6}{120} + \frac{5}{80} + \frac{0}{20}\right) \doteq 0.0375 \doteq 0.04.$$

H.3.5 Summary

We compare the numerical results from the three methods for calculating confidence limits for the access failure probability of Network A:

Method	d.f., f	Point Estimate	95% Confidence Limits	
Among trials	219[8]	0.050	0.01	0.12
Among tests	10	0.045 or 0.050	0.01	0.10
Among cities	2	0.035 or 0.038	0.0002	0.13

The procedure for obtaining failure probability confidence limits is the same as in Section H.2.5 for time performance parameters except for the initial case in Section H.3.2 of pooling all trials together, which is tested with the chi-squared test (19) and (A-58) of Miles (1984). If pooling is permissible, the limits are calculated from (A-31) of Miles (op. cit.). If pooling is not permissible, the data are transformed by (18), and the procedure of Section H.2.5 (iii), (iv), and (v) is followed.

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15. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

This report presents results of a multiyear data communication performance measurement program conducted at the Institute for Telecommunication Sciences, the research and engineering arm of the National Telecommunications and Information Administration. This program had two specific objectives. The first objective was to develop a comprehensive, automated performance measurement system capable of assessing data communication performance in accordance with American National Standards X3.102 and X3.141. The second objective was to demonstrate a successful application of this new system in assessing the performance of connections established over representative public data networks and switched telephone networks.

This report describes the performance measurements conducted in accomplishing the assessment demonstration objective of the program. The measurements were carried out using a computer-based system that collects and processes performance data to produce estimated values of ANS X3.102 parameters, together with a variety of graphical displays of measurement results. The report includes descriptions of the design and conduct of the measurements and an extensive presentation of performance values.

Key words: American National Standards; data communications; confidence limits; end users; performance measurement; switched networks

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