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COMPUTER NETWORK RESEARCH

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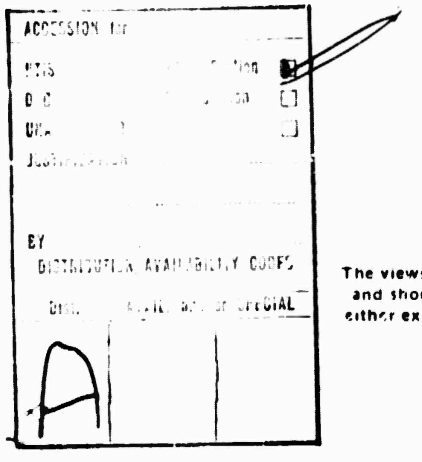

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This is the final report for the ARPA Contract number DAHC 15-69-C-0285 at UCLA covering the period from April 1, 1969 to December 31, 1973. The research conducted during this period covered the following areas: analytic models of computer systems; analytic models of computer-communication networks; design methods for computer communication networks; measurement of computer-communication networks; packet switching for satellite communications; packet switching

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for ground radio communications; and computer system security. Included is a short statement of accomplishments followed by a complete bibliography of published works which were supported under this research contract.

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COMPUTER NETWORK RESEARCH

FINAL TECHNICAL REPORT

December 31, 1973

ARPA Contract DAHC-15-69-C-0285

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Program Code No. 9D30

Principal Investigator: Leonard Kleinrock

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COMPUTER NETWORK RESEARCH

Advanced Research Projects Agency
Final Technical Report

December 31, 1973

This final report covers the period from April 1, 1969 to December 31, 1973 for ARPA contract number DAHC 15-69-C-0285. The research conducted during this period has been amply reported in our semi-annual technical reports as well as in the published literature. Consequently, the format of this final report is quite simple and brief. In the next few paragraphs we discuss the major areas of research and the principal results which have been obtained therein. The technical content of these results and of this research is not discussed in detail here, but rather the reader is referred to the extensive bibliography which contains entries, all of which were supported by this ARPA contract. The research in these areas continues and is currently being supported under ARPA contract number DAHC 15-73-C-0368.

The original goals of this contract were succinctly stated in our proposal of November 1968. Below we repeat the general statement of those goals and our expanded view of the tasks involved.

> "The main purpose of this contract shall be to engage in those activities which enable UCLA to participate as a viable, creative, and significant node in the ARPA experimental computer network. These activities include:
>
> > Implementation of hardware and software to couple the UCLA HOST to its IMP;
> >
> > > We are starting the hardware design for interfacing with the IMP to provide a data path to and from the HOST. This will proceed at a faster pace once the more complete IMP specifications are provided. This work will be scheduled so as to make it possible for UCLA to participate in the initial four-node net.
> >
> > Research in the development and use of analytical and simulation models of computer networks and time-shared computer systems;
> >
> > > Our activities in mathematical modelling of communication nets, computer nets, time-shared systems and multi-computer systems will continue at an increased level of support. The same is true of our simulation models which will grow in sophistication as more details internal to the IMP structure are made known to us. In this same connection, more suitable simulation procedures and languages will come under study. We recognize that the macroscopic view of

the general flow of data in the net is important. We intend to study the effect on this flow due to changes in routing algorithms, network configurations, shifts in demand, IMP storage, error rates, etc.

Development of software procedures for active participation in the initial and full ARPA net;

The software system necessary for IMP-HOST and HOST-IMP transfer will be developed early in the contract period. The second stage of software development will be in preparing UCLA sub-system programs for network users as well as preparation by UCLA for use of the initial four-node (and later 19-node) network program environment. This will include some expansion of our new time-sharing executive system (SPADE).

Develop software suitable for measuring those network parameters which allow one to understand network behavior, which allow control of network functions and which permit us to assess the validity of our mathematical and simulation models;

The existing measurement software system will be extended to enable network measurement of various types in order to gain an understanding of the network behavior. These measurements will be used both for controlling the network (through its routing procedure, calling protocol, etc.) and for assessing the validity of the mathematical and simulation models.

Carry out studies on the use of remote facilities in a network environment.

We will also conduct studies of methods by which sufficient information about a remote computer can be obtained through a network to permit intelligent use of the remote installation."

The goals stated above have by and large been achieved with success, and other unpredicted but related goals have also been studied and have generated important results. Below we discuss these results, broken down by topic and keyed to the bibliography. This ARPA contract has resulted in the completion of six Ph.D. dissertations, six MS theses, 54 published papers, and a very large number of presentations at conferences, seminars, and symposia.

The first topic we consider is that of Analytic Models of Computer Systems. Our effort at UCLA is perhaps the best known around the world for our early and continued work in this area. We produced and solved the earliest models for time shared computer systems focusing originally on the single resource model for these systems. Lately our group has been most instrumental in generating analytic models for multiple resource time-shared and multi-access computer systems. The numerous papers and

reports which have resulted from this effort are listed in the first section of the bibliography following. The effort here has been extremely successful and has motivated other research groups around the world to engage research in this area.

The second topic is Analytic Models of Computer Communication Networks. This is also one for which our group at UCLA is world famous. Again, we produced some of the earliest models describing the behavior of computer communication networks and these models continue to form the basis for all of the analytical and design technology which has recently emerged. Principal works which have resulted from our effort are listed in the second section of the bibliography. Here we have developed some rather sophisticated models of network behavior, and we have constantly refined these models as a result of our experience of the ARPANET. We have been able to show that our models correspond very well with the simulation and measurement results of real traffic.

Next, we consider Design Methods for Computer Communication Networks. These recent design tools represent one of the successful aspects of the ARPANET experiments. Indeed, we now understand what is involved in creating a packet switching network and are able to describe design tools which lead to efficient networks. Our effort here has resulted in an heuristic approach to the topological and overall design of networks, and has led to a number of sub-problems, each of which, has been carefully solved and documented. Again, the major results, here are listed in the third section of the bibliography.

The results for our fourth topic, Measurement of Computer Communication Networks, we derived from our function as Network Measurement Center for the ARPANET. This effort has been a relatively high overhead task during its early stages due to the need to develop extensive measurement tools and measurement programs prior to the experiment phase itself. During the latter phases of this contract, we have begun to see many more significant experiments and results coming from the Network Measurement Center (and this has accelerated considerably in the Network Measurement Center's efforts during the new contract period). Earlier, we were responsible for influencing BBN's IMP operating system design with respect to the inclusion of rather extensive measurement tools within each IMP. These tools have made possible the sophisticated and revealing experiments which we have been conducting. The fourth section of the bibliography points to these results.

A more recent activity which we had not anticipated at the start of this contract, but which became important to ARPA and of interest to us during the latter phases was that of Packet-Switching for Satellite Communications. Here, we have played an important role in the analysis of the behavior of multi-access broadcast satellite channels. A rather sophisticated model has been developed and analyzed with some approximations which have been supported through simulation. Moreover, we have developed some optimal control procedures to stabilize the basically unstable slotted Aloha access mode. The publications and reports emanating from this research are listed in the fifth section of the bibliography.

A research area related to Satellite Packet Switching is that of Packet-Switching for Ground Radio Communications. Here too, we have played an important role in providing the basic analysis for a new access mode known as Carrier Sense Multiple Access. This effort has been picking up strongly in the new contract. The publications and reports are listed in the sixth section of the bibliography.

The last major activity we have been involved in is that of Computer System Security. This effort was completely unanticipated in our original proposal but has become an area of basic importance to the proper functioning of computer systems and of computer networks. The research here is extremely difficult and our approach has been to provide a procedure whereby systems can be proven secure rather than just tested (an endless task) for security. The pertinent publications are listed in the last section of the bibliography.

In summary then, we offer as the final measure of our achievements during this contract period, the publications listed below. In addition to these printed documents, however, we have been functioning as active participants in the growth and development of the ARPANET at many levels. The success of the ARPANET has been in part due to the distributed responsibility for a variety of unnamed tasks and unforeseen needs; in this too, we have borne far more than our share.

The following bibliography is made up of 58 papers, 6 masters' theses, 6 Ph.D dissertations, several book chapters and numerous presentations, notes and memos.

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