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COMPUTER NETWORK RESEARCH
FINAL TECHNICAL REPORT

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November 30, 1975

COMPUTING SYSTEMS
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This is the final report for the ARPA Contract number DAHC 15-73-C-0368 at UCLA covering the period from June 15, 1973 to November 30, 1975. During this contract period we have been engaged in the following tasks: providing a sophisticated network measurement facility adequate for a variety of uses such as performance measurement, model validation, and the design of network algorithms; conducting experiments on the network to analyze the effect of

Next Page

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) transmitting various data sources; defining and extending the tools necessary to analyze and evaluate the performance of computer communication systems; developing models of multiple resource systems and computer networks; studying packet communication systems that incorporate satellite and/or radio communications; and designing and beginning implementation of a verifiably secure operating system for the PDP 11/45. 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

November 30, 1975

ARPA Contract DAHC 15-73-C-0368

ARPA Order No. 2496
Program Code No. 3P10

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COMPUTER NETWORK RESEARCH

Advanced Research Projects Agency
Final Technical Report

November 30, 1975

This final report covers the period from June 15, 1973 to November 30, 1975 for ARPA contract number DAHC 15-73-C-0368. 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 as was the final technical report for ARPA DAHC 15-69-C-0285. In the next few paragraphs we discuss the major areas of research and the principal results which have been obtained therein. The technical contents of the results of this research are not discussed in detail here, but rather the reader is referred to the extensive bibliography of entries, all of which were supported by this ARPA Contract. The research in many of these areas continues and is currently being supported on a continuation of ARPA contract DAHC 15-73-C-0368.

During this contract period we have been engaged in the six tasks listed below:

Task 1: Provide a sophisticated network measurement facility adequate for a variety of uses such as performance measurement, model validation, and the design of network algorithms.

Task 2: Conduct experiments on the network to analyze the effect of transmitting various data sources.

Task 3: Define and extend the tools necessary to analyze and evaluate the performance of computer communication systems.

Task 4: Develop models of multiple resource systems and computer networks.

Task 5: Study packet communication systems that incorporate satellite and/or radio communications.

Task 6: Design and begin implementation of a verifiably secure operating system for the PDP 11/45.

These tasks have all advanced significantly during this period. The output of this research has appeared in the form of three Ph.D. and three Master's theses as well as 43 publications of the principal faculty, staff and students which have appeared in the professional literature. These publications are listed in the bibliography below. That bibliography and the research areas are grouped as follows:

(1) Analytic Models of Computer Systems

(2) Analytic Models and Design Methods for Computer Communication Networks

(3) Measurements of Computer Communication Systems

(4) Packet Switching for Satellite Communications

(5) Packet Switching for Ground Radio Communications

(6) Computer Systems and Security

In the field of analytic models of computer systems, we have made major progress in the modeling of multiple-resource models of operating systems. We are now capable of identifying system bottlenecks, calculating throughput and delay and suggesting system configuration. This work is based on queueing network models of multiple resource operating systems. We have been able to gernalize these models to include much of the realistic behavior of these systems. The costly errors of the past need no longer be made, and intelligent design can now be done. The cost-effectiveness of proposed design options and changes can now be evaluated.

In the field of analytic models and design methods for computer communication networks we have made significant progress in the optimal allocation of capacity of distributed computer networks, specifically in the case where channel capacities must be drawn from a discrete set. This is an important result in a realistic problem in computer network design; the solution in this case is important. We have further identified some of the key issues and challenges in computer networks and have laid out the path of research for many years to come. We have also made progress in the use of algorithmic methods in combinatorally complex problems which are needed in computer systems analysis. We have extended the algorithm for finding minimal spanning trees in networks which considerably reduces the cost of running the algorithm. We have proven that there are very significant gains to be had with large shared systems. This has been demonstrated mathematically for a reasonably broad class of systems and we are currently extending that class. In particular, we have shown that as one scales up the system capacity and the throughput of any finite-capacity system, then the delay in passing through that system decreases by the same scale factor. We have shown this as a bound for general systems and as an exact result for more specific systems. The significance here is on the design of processing and communication systems. "Bigger is better" seems to be the message when the question is posed correctly. The exact form of these results and their impact on system design will bring considerable light to cost-effective system design.

Our measurement of computer communication networks has been fruitful and has exposed many interesting phenomena. As a result of our activities as the Network Measurement Center (NMC), we have predicted and/or observed numerous and serious deficiencies with the ARPANET throughput, i.e., network deadlocks and degradation. We predicted the "piggyback allocate" deadlock condition by examining the IMPSYS code and provided a solution to it which BBN has implemented. The famous "Christmas deadlock" was exposed as a result of experiments performed by the NMC; this deadlock occurred due to a lack of pointers to allocated buffers in the destination IMP and has since been corrected. As a result of our packetized speech experiments in which we measured single-packet throughput, we identified serious degradation due to out-of-order packets in the data stream. Furthermore, we identified the source of unacceptably long delays as being due to persistent looping caused by the routing procedure; we have found a loop-free solution to this problem. Analysis and measurements of the effect of network overhead on the performance as seen by the user have been conducted. We find that what appear to be harmless options offered to the system implementers can have significant effects on network performance. We have identified a number of these and have pointed out how they should be restricted in order that really major improvements (one to two orders of magnitude) in network throughput be achieved. The overhead on the communication lines due to the various levels of protocol have been found to have profound effects on throughput. The whole mechanism of allocating buffer space in the destination HOST and in the destination IMP must be very carefully examined. We find that the maximum line efficiency is roughly 80% under the most ideal conditions, and that it is as low as 1% under very common conditions. If the current traffic patterns continue, then we can obtain only 20-25% line efficiency in the ARPANET.

The exciting area of packet switching for satellite communications as well as ground radio communications is a new and rapidly growing field of investigation. We have been successful in evaluating the performance of packet switching in satellite communication systems and also in ground radio systems. The slotted ALOHA analysis is quite advanced and now provides a classical model for system analysis. We have analyzed the basic unstable behavior of slotted ALOHA in the infinite population case, and have defined and analyzed the stable and unstable modes in the finite population case. In the latter situation, we have calculated the average time until the system goes unstable. Further, we have found OPTIMAL control policies which render these (unstable) channels stable. Realistic estimation and heuristic procedures have been developed which allow a practical implementation of these control procedures and they have been shown to be quite effective in the throughput-delay-stability tradeoff. The carrier sense access mode for ground radio has been completely analyzed in the single hop case; that access mode has been shown to be superior to slotted ALOHA. The serious problem of hidden terminals has been analyzed and the busy-tone solution to this problem has been shown to yield performance which is only slightly degraded as compared to a system with no hidden terminals. Furthermore, a reservation scheme for using the ground radio channel has been suggested and analyzed and appears to offer significant advantages over an important operating range. These random access modes offer distinct advantages over the more classical access modes when the traffic is bursty (as with terminal traffic and other interactive traffic). With the simple slotted ALOHA method as compared to the classical FDM methods, we find that we can reduce the required bandwidth and/or increase the number of users and/or reduce the delay over a wide range of system parameter choices; these advantages are even greater with the use of carrier sense.

In the field of principles of secure computing, a number of results have been obtained. The bulk of that work falls into three major categories: security design principles, security verification and certification, and prototype development. The majority of the design principles concern operating system structures. Strong evidence has been developed which argues that the traditional practices of placing supervisor code into user tasks, as well as locating virtual memory support at lowest system levels, are design flaws with respect to security. The simplifications provided by virtual machine designs are now reasonably apparent. Progress has been made in developing greatly simplified approaches to I/O handling, usually one of the most serious sources of security flaws. Subtle, generic communication paths in systems have been identified. In addition, the general principle of "least common mechanism" was developed and illustrated. Work on verification and validation of security software has now progressed to the point where it is clear that the approach is viable. Security assertions, which precisely define the notion of data security, have been specified. The first pass at a semantic model of the security kernel, in which the detailed proof takes place, has been completed, and work on the actual proofs has begun. Pitfalls and inadequacies in standard verification strategies have been found and extensions to those methods outlined. Considerable prototype development has already occurred, and that development has been successful in motivating a number of results described above. The design of a complete, practical, verifiable security kernel has been completed. Parts of that kernel code are now debugged and running. Design of the virtual machine monitor, which runs over the kernel, is also complete. Substantial portions of that prototype software are also debugged. Operating systems such as ANTS and DEC standard release DOS have already been successfully run in virtual machine environments.

In summary, then, we offer as the final measure of our achievements during this contract period, the publications list below. This bibliography consists of 43 papers, three Master's theses and three Ph.D. dissertations. In addition, two major books have been published which are based in part on the research conducted on this contract.

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