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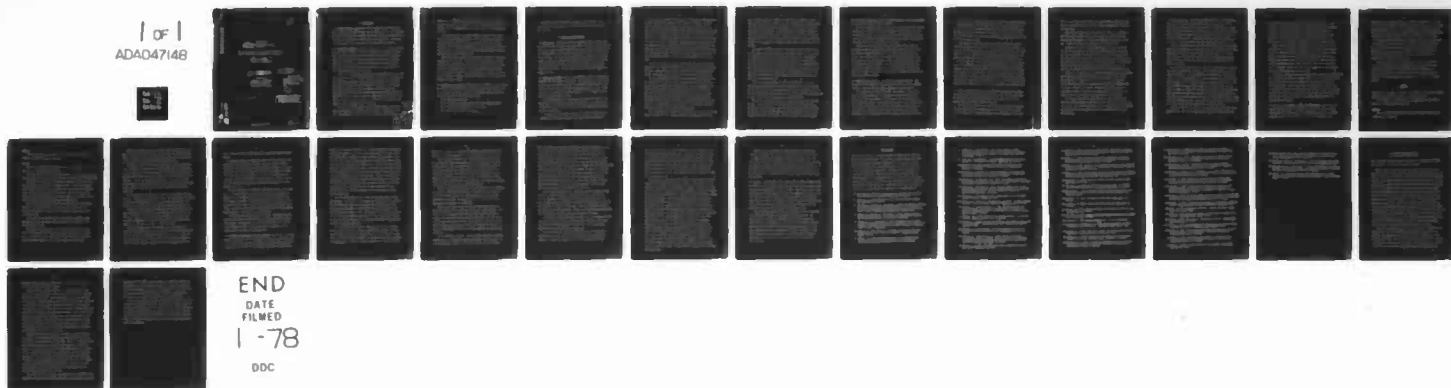RESEARCH INTO QUEUEING NETWORK THEORY.(U)
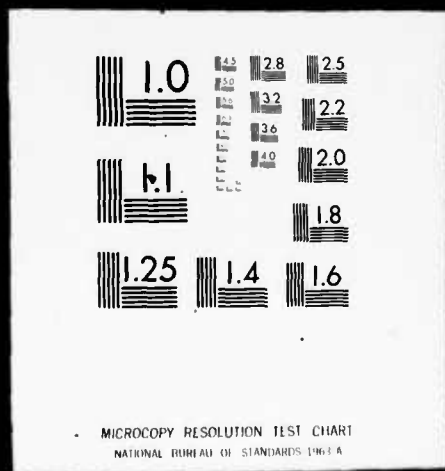SEP 77   R L DISNEY   N00014-75-C-0492
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ONR Contract

15. N00014-75-C-0492 (NR042-296)

6. Research Into Queueing Network Theory.

9. Final Report.,

11. Sep ▮▮▮ ▮77

12. 28 p.

Submitted by

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1.   Introduction

1.0   Contract History.   Research on contract N-00014-75-C-0492 (NR042-296) was initiated in modification A00001 (dated 5 February 1975) to the previous contract number N00014-67-A-0181-004 (NR042-296).   Modification P00002 (dated 18 March 1976) extended the contract period to 31 August 1977.   This paper is a final report on the activities accomplished under the contract.

1.1   Evaluation of Research.   Research under the contract has been concerned with both the development of theory and applications of queueing networks. Prior to 1964 there were few results available for the study of queueing networks.   Since 1964 the field of queueing networks has developed into a major field of study for both its theoretical interest and its applied interests.   A history and critique of developments both before and after that time were reported in [17] and [55].

We have used the knowledge gained from the theoretical studies to assist in the study of a number of applied problems.   These include: the design of a police-ambulance emergency vehicle dispatching system;   the design and evaluation of a medical screening program for colo-rectal cancer; design and analysis of computer scheduling schemes; evaluation of computer simulation models of large scale defense communications systems; models for command and control systems for naval air combat missions; analysis of road traffic flow on superhighways; analysis of curb parking facilities in the design of airport passenger traffic facilities.

In addition, knowledge gained from our queueing network research has achieved international recognition and is serving as background material to further research by others in the area as well as to applications of

these results. While we are not aware of all of the references using our results, we are aware of some of them. The work of Fujisawa, et.al. (for example, see [27]), Lemoine [35], and Kobayashi, et.al. [34] illustrates the point.

Statistical analysis of computer simulation is an area to which our research can have a significant impact. The most commonly used method of studying stochastic systems, notably queueing networks, is by computer simulation. It is becoming increasingly clear that statistical analysis of simulation data is a major area that requires deeper knowledge of network random processes than we currently have.

That the problem of statistically analyzing simulation is difficult is attested to in [9] and [21]. That there are known properties of random processes that could assist in solving some of these problems is attested to in [19], for example. Thus, not only has the research effort made a direct contribution to the theory and applications of queueing networks, it has the potential of making a significant contribution to data analysis in computer simulation studies.

1.2 <u>Research on this Contract</u>. Research under the specific this contract number of section 1.0 has been comprised of several subareas. The following is a terse listing of the areas. They will be discussed in greater detail in the following report in the indicated sections:

(2.1) Queues with Feedback;

(2.2) Simplification, Approximation and Flow in Jackson Networks;

(2.3) Queues with Deterministic Service Times; and

(2.4) Applications of Known Results,

Research in all of these areas is ongoing as will be noted. Much of
it will be continued in the future by researchers who are now working on
the contract.

2. Research Accomplishments

2.0 Introduction. As noted in Section 1.2 research under the contract has
been conducted into four major areas noted there. Research has been previously
discussed in project Technical Memoranda all of which have been distributed to
the designated offices and people on the contract mailing list over the life
of the contract. Therefore, we will summarize the contents of those papers
relevant to each above topic without going into detail as to their content.
In the Bibliography (Section 3) we will call attention to those reports
previously distributed. In each subsection below we will also comment on
ongoing efforts.

2.1 Queues with Feedback. There is a considerable interest in queues with
feedback, both theoretically and applied. [55] references over 200 articles
many of which are concerned with what in the computer modelling literature
are called "round robin queues" and "foreground-background queues". These
types of queues all have some kind of feedback structure imposed on items
that have already received service.

An investigation of these systems was conducted in [10] which had the
added feature that feedback occurred instantaneously. This assumption is
in agreement with the one made in nearly all queueing feedback studies with
which we are familiar.

It seems to be "well known", though until recently we could find no
supporting investigation to prove it, that when feedback is added as a

feature to any queueing network, flow in the network takes on some unexpected aspects. Kleinrock [33] comments on this result, for example. In 1976, Burke [6] provided the first proof of some of what was occurring in the flow in these instantaneous feedback systems. The most detailed investigation here occurs in the Disney and McNickle paper [20]. Though the results are special cases of Davignon [10], they have proven to be of sufficient importance to warrant a separate investigation. Furthermore, because the system studied is comparatively simple, the heavy analysis of Davignon is unwarranted. This means that the Disney and McNickle study can produce more intuitively appealing and understandable results. Neither [10] nor [20], however, is restricted to Jackson networks as seems to be true of all other feedback studies except [52].

In effect the Disney and McNickle results show that the flow of items inside of a FCFS, single server queue with Poisson arrivals and instantaneous Bernoulli, feedback is never a renewal process even in those cases of M/M/1 queues. This result makes the classic result of Jackson [29] surprising.

In [43], Melamed conjectured that in any Jackson network in which there is a loop from one server back to that same server, flow on that path was neither a Poisson process nor a renewal process. In [44], Melamed has now firmly established that in Jackson queueing networks flow on paths that exit from the network are Poisson processes and if such exit flows occur from more than one server in the network, the several flows are mutually independent Poisson processes. He has now also established that flow along any arc in the network that forms a loop back to a given server, is never a Poisson process and indeed is never a renewal process.

This result brings the study of flow in Jackson networks to an interesting point as discussed in [20]. Deeper exploration of these results even for

simple Jackson networks is required. In particular, the Melamed results
demonstrate clearly that at least along arcs of feedback in a queueing network
one cannot remove any one server and analyze it as a subsystem using M/M/1
queueing results independent of the remainder of the network as seemed to
be implied by Jackson [30, pp.520]. Thus to properly study such a server in
isolation one must at least consider queues whose arrival process is a Markov
renewal process possibly on a complicated state space (as is done in [36], for
example).

The idea of studying each server in a Jackson network as though it were
an M/M/1 queue is a practice that is not uncommon in application (e.g., see
the arguments to defend such an approach in Nakamura [45]). The Melamed
results coupled with the Disney and McNickle results not only demonstrate
that such analysis must be done with great care (and cannot be done formally
for networks with loops) but also demonstrates what type of analysis must be
done when that approach is inapplicable. These developments thus add a new
dimension to queueing theory that should have significant implications to
both the theory and application.

There is considerably more that needs to be done here. It can be
conjectured, though there are few currently known results, that the feedback
random process and the arrival random processes are not independent processes.
But how these processes are dependent, if they are, and thus what the superposed
process of the two is, is an important area of investigation.

Disney and McNickle conjecture the feedback process is not a Poisson
process. They do show that the departure process for M/M/1 queues with
feedback is a Poisson process. Since the output process is a Markov renewal
process one asks how a "dumb" switching process (a Bernoulli trials process)
can possibly produce these results. One must conjecture that the feedback

process and the departure process are dependent processes. But how they depend on each other is totally unknown at present.

Our present knowledge tells us little about the properties of the feedback stream itself. We know it is probably dependent on the arrival process and the departure process. We have a form (which is given in Disney and McNickle [20]) for the distribution of single intervals in this stream. This is about the current level of our knowledge of this process.

Finally, for the problem of queues with feedback, when an item that eventually returns to a given server first passes through other servers (as for example in Jackson networks with loops) that item is delayed on its return. All current knowledge about queues with feedback presupposes that such feedback occurs instantaneously. Nearly nothing is known about flows in networks with delayed feedback. For this reason, the study of queues with delayed feedback has begun under the current contract. This ongoing work will continue. At present, it is too early to present any results newer than those presented in [28].

2.2 Simplification, Approximations, and Flow in Jackson Networks. This activity has been primarily directed towards the class of Jackson queueing networks. There are two main themes: analysis and simplification.

The analysis part is described in [3], [42] Chapter 4, [5] and [43] while the simplification part is summarized in [52] and [42] Chapter 5. This combined work was based on the presumption that the two-tier study could benefit both areas. Thus simplifications could be used to facilitate the analysis of complex networks by valid reductions to simpler cases; on the other hand, the study of various aspects of networks could provide additional tools to simplification efforts, when the situation calls for it.

The study of Jackson networks is largely devoted to equilibrium analysis of line lengths and traffic processes as well as the relations between them. As a matter of fact the former is characterized in terms of a simple linear equation in terms of traffic rates ([3], [42]). More generally, a duality between line lengths and traffic is now beginning to emerge which has received but scant attention so far.

Considerable attention has been paid to traffic processes in Jackson networks; the main interest here is to study conditions that insure that such processes are Poisson processes. The importance of Poisson traffic processes stems from the applications of this knowledge to network decomposition. We shall revisit this point when discussing network simplifications later on.

It was found (c.f. [5], [43]) that the feasibility of a Poisson process on an arc in equilibrium has a simple characterization in terms of network topology; that is the traffic process on arc (a,b) is Poisson in equilibrium iff arc (a,b) is an exit arc (i.e., there are no loops that enable customers that leave node a to return to it). See Section 2.1 for a further discussion. Surprisingly, it was found that for traffic on arc (a,b), the renewal property alone and Poisson distribution alone are each equivalent to a Poisson process.

Other characterizations as well as a measure of the deviation of traffic on a nonexit arc from the Poisson were derived in [43]. These results point at the validity of Poisson approximations of every traffic process in a Jackson network under heavy traffic conditions.

In the second line of study, we begin by defining precisely the concept of system simplification. A simplification is an operation on the system such that a new system is obtained subject to two requirements. First, the

new system must have a reduced complexity (with respect to some complexity notion), and second, some aspects of the original systems must be preserved (in some sense).

Some simplifications studied (cf. [41], [42], [43]) were: removal of arcs from a given network, lumping sets of nodes into single nodes, and decomposition that enable us to study each component separately in a valid way. A variety of preserved aspects has been identified, [42].

As stated before the Poisson process property of traffic on arcs is the clue to the feasibility of decomposing a Jackson network into Jackson subnetwork components. It was found in [5] that the partition induced by the communications relation on the node set constitutes a decomposition into Jackson subnetworks, provided the network is in equilibrium. It was further found in [43] that this decomposition was maximal in the sense that no refinement of the aforementioned partition could yield Jackson subnetworks.

A very general methodology for constructing simplifications in stochastic systems and identifying preserved aspects was developed in [42]. This methodology employs measure preserving transformations on probability spaces whose sample spaces are represented by deterministic automata, each modelling a certain system history. The methodology, however, is not algorithmic; rather, it provides the relevant sufficient conditions. An application to Jackson networks is demonstrated in [42], Chapter 5.

The foregoing research has paved the way to a study of generalized notion of traffic processes in Markovian systems. Such a study is currently in progress. This study has wide applications to Poisson traffic in Markovian queueing networks, and consequently it will have ramifications to their decompositions.

A generalization of the traffic equation (see [3], [42]) for Markovian systems is now also beginning to emerge. This research effort is now directed to relating and explaining the connection between the equilibrium state distribution and the generalized notions of traffic and traffic equation above, especially as regarded the duality between line lengths at nodes and traffic processes on arcs. This latter research is still in progress. It is too early to give newer results than those in this section (but see [44]).

While the Jackson networks discussed above currently contain the single most widely used results, it is quite clear that such networks are not nearly encompassing enough even for the computer studies to which they are most often applied. Several attempts to generalize those models have appeared in the literature recently (e.g., [2], [31]) and one expects this area to continue to develop.

As we have shown many times (e.g., see [17]) one can think of a network as a collection of operators that map a set of random processes (called the arrival processes) into a set of departure random processes. Properties of the arrival processes and properties of how the operations are to perform are assumed known. One of the basic questions of queueing network theory is how the operations alter the stochastic properties of the arrivals. In very imprecise terms, it appears that the operations (decomposition, recomposition, and stretching) that have been considered in queueing networks map arrival processes that are Markov renewal processes into other Markov renewal processes called the departure streams. Thus, in some sense this Markov renewal property is preserved by the queueing networks that are usually studied.

Because of the inherent complexity in studying queues with Markov renewal arrivals (e.g., see [36]) it seems natural to seek for simplifications to

such problems and approximations to them. There are two rather distinct
paths that this search can take. In one of these one seeks to find renewal
processes that are "almost the same as" the Markov renewal process of
interest. In the other, one seeks to find simple queues whose queueing
properties are "almost the same as" those with Markov renewal arrivals.
Whether these two approaches are equivalent or not is at present unknown.

Under the current contract we have begun to explore the first of these
two approaches. In particular, research is being conducted into developing
a theory of lumpability of Markov renewal processes. We are seeking in partic-
ular to discover conditions (hopefully necessary and sufficient) under which an
m-state Markov renewal process is equivalent to either a renewal process or
to smaller dimensional Markov renewal processes. This work is very early
in its development. Results here have not been formalized yet into a report.
Such will be done before the end of the year.

In summary, considerable progress is being made in the area of simplification
and approximation of queues in networks. Much of this work is well developed.
Other work is still in its most formative stage and is not yet ready for
open dissemination. If this latter line of investigation is fruitful, and
we are hopeful based on the currently available results, then work on queueing
networks can be translated into practical, usable form that will considerably
ease the job of using the results for the study of ongoing systems (e.g.,
computer network studies).

2.3 Constant Server Queues and Packet Switched Networks. In II of the ONR
proposal [18] we were asked to consider the influence of constant service
time service facilities on a model of a communications network as a network
of queues. There are two reasons for this. First, the "independence

assumption", where message lengths are re-assigned randomly at each node, is one of the most unsatisfactory assumptions required to the solution of networks by Markovian models (see [32] for this assumption). Second, while a Poisson model for first-offered traffic is apparently acceptable a negative-exponential distribution for message lengths is not usually encountered. The current trend towards packet-switched networks, especially in computer networks, where each message is divided into packets of constant length to be transmitted over a store-and-forward network, clearly makes use of $\cdot/D/1$ models mo.e appropriate than the often used $M/M/1$ models. Considerable progress has been made in these constant service time queues. The work to date is summarized and brought up-to-date in [40].

Consideration of a series of identical service facilities shows one of the problems of exponential service distribution. If the initial input is Poisson with parameter λ then an exponential service assumption gives identical mean delays at each facility, whereas if the service times are constant, d, no waiting occurs at any facility but the first, and the mean delay is

$$\frac{\lambda d^2}{2(1-\lambda d)} \, ,$$

independent of the number of stations. This dominance of the first or slowest facility was formalized by Avi-Itzhak [1] and Friedman [26].

Some insight can be gained from the following remarks, which seem to govern all the easy results in this area.

Remark 1

Only an arrival who initiates a busy period at server d_1 can initiate a busy period at server d_2.

Remark 2

All arrivals served in a particular busy period at server d_1 must be served in the same busy period at server d_2.

Remark 3

The busy period and idle time process at server d_2 is governed only by the sequence of arrival times at server d_1.

It appears that the mean delay and output results of Friedman and Avi-Itzhak still hold when the system is not FCFS, provided the discipline is work-conserving.

The results of Avi-Itzhak and Friedman are apparently not well known and were re-presented by Rubin [46] for Poisson arrivals. In Rubin [47] complex expressions are found for the distribution of the waiting time at intermediate nodes. These do not appear to be very tractable. Rubin [48] places these results in a packet-switching context by using a batch Poisson arrival process with variable batch size corresponding to the message length.

None of the previous models allows for the introduction of first-offered traffic (or traffic carried from other parts of a network) at any node. Previously this problem has proved almost intractable except in the case of Markovian networks.

Network problems can be divided into 3 sub-classes of problems; superposition, switching, and output. This division has proved appropriate in the packet-switched area.

The problem of superposition of first-offered and carried traffic was first considered in Rubin [49] who found approximate mean delays for single packet traffic at such nodes. These could only be included in a network in a very approximate fashion, since the output character was not found.

Generally his method consists of looking at each stream separately and modifying the service time to account for interference, to give approximate results. These turn out to give reasonable approximations, but would only be useful for small systems because of the cumulative error.

In McNickle [40] it was shown that under certain conditions mean delay with interference is preserved by re-ordering stages. This was generalized to n input processes, batch Poisson inputs with different distributions, all feeding a single server with service time d. Provided the constant service times d_i, i = 1, 2, ..., n have the property d_1, ..., $d_n \leq d$, the output and mean total wait in the system are those of an M/D/1 (batch arrival) queue. An upper bound for the mean delay when this condition does not hold was suggested.

We conjecture that the mean delay remains the same regardless of the order of stages for any values of d_1 and d_2. The superposition is replaced by a Bernoulli decomposition switch with appropriate probabilities. The results still hold when a finite waiting room is inserted in front of d_2.

Based on the three remarks made previously the results of McNickle [40] may be extended to arbitrary inputs. For identical service times and two independent inputs this result was proved by Ziegler and Schilling [56]. We conjecture that when the inputs are independent the mean delay result holds in the limit for $d_i \leq d$, d_1, ..., d_n not identical.

Rubin [49] suggests that for a Bernoulli switch decomposing the departure stream from server d_1, an approximation for the mean waiting time at d_2 can be found by considering the traffic that enters server d_2 only. We conjecture that this result is in fact a tight upper bound. Since an orderly arrival process usually gives a lower mean waiting time a

lower bound can be found in some cases from an appropriate multiple-server system.

A numerical package for determining delays in simple constant service time queues would seem highly desirable. This should handle multiple servers, at least two stations in tandem, dependent switching, and possibly priorities. Few results are known for even the $GI/D/1$ queue, for example, so the generality of the Friedman and Avi-Itzhak results cannot yet be exploited. Analytic investigation of simply models of this type could also be tried. Existing analytic results would make the validation of such a package very easy.

We are in relatively good shape for interference results. A procedure for the case where some of the d_i's are greater than d was suggested in McNickle [40]. The conjecture that this gives an upper bound could be investigated numerically. Of particular interest is the question of the delays of different types of traffic, first offered versus carried; and so forth. In military traffic priority classes with different message lengths may be important. This remains to be investigated.

In switching networks much remains to be done. Consideration of the possible reversibility of order of nodes (preserving mean delays) may be one approach. More general switches must be considered. With multiple-packet messages the switch will obviously not be Bernoulli, since the destinations of packets are highly correlated.

2.4 Particular Applications to D.C.E.C. Networks. In addition to the work reported in Sections 2.1 - 2.3 the members of the project have devoted time to the solution of specific problems posed by DCA/DCEC concerning problems in queueing network theory that are directly applicable to the modelling

activities of D.C.E.C. Results of some of these investigations have appeared
as Discussion Papers of the project rather than Technical Memoranda. These
Discussion Papers are intended to answer, directly, problems posed to us by
D.C.E.C. In one case the question posed led to a significant research effort
(which is still in progress (see Section 2.3)). In other cases the questions
posed led to the Discussion Paper only. In one other case the question posed
requires considerable research effort and this research is still in progress.
It has not appeared in any project document yet. Finally, one collection of
questions was answered through a series of verbal exchanges and interchange
of information that was developed some time ago in other research projects.
These inputs will be incorporated into a document prepared by D.C.E.C.
personnel directly. The topics covered by all of this research include
the following items:

2.4.1 Discussion Paper QT 76-1. This was the initial paper written
for DCA/DCEC. It contains a brief discussion of DCA/DCEC procedures, models
and the simulations used in the evaluation of the DCA computer networks.
The paper is a consequence of the assignment of one project member to the
DCEC offices in the summer of 1976. The purpose of the visit was to acquaint
us with the computer modelling activities of D.C.E.C. This paper served as
a basis for discussion with D.C.E.C. to make sure the project understood its
activities in computer modelling.

2.4.2 Discussion Paper QT 76-2. This paper was the first to appear
on the subject of queueing networks with deterministic servers. The topic
was originally posed by D.C.E.C. personnel and is discussed in [18] in some
detail. QT 76-2 was updated, ammended and expanded as the research developed.
These modifications appear in Discussion Papers QT 77-1, 77-5 and Technical

Report 77-3. Section 2.3 of this report summarizes Discussion Paper QT 77-5
which is a review and updating of this line of research as of 31 July 1977.

2.4.3 Discussion Paper QT 77-2. Jackson networks of queues are the
most common of queueing network results that have been applied to computer
systems. If one allows no storage facilities in a network but retains all
of the other assumptions of Jackson networks one obtains a larger vector
valued Markov process. Each vector describes the configuration of jobs in
progress in the network as a function of time. If these Markov processes
could be handled computationally, an important step could be made to simplify
the analysis of a very useful class of computer models.

Using the infinitessimal generator of the Markov chain one can represent
the chain as a weighted, directed graph. It was hoped that by this means
one could obtain the computational tractability that has so far eluded
researchers in the field. Discussion Paper QT 77-2 is the result of an
exploratory investigation of this approach.

Based on that study, it does not now appear that those methods will
produce the desired results unless the network has a simple topology. For
that reason the Discussion Paper should be viewed a noble experiment in
research that will have to be down-played in the future. It is not likely
to yield major new results, directly. There are still useful ideas in the
approach (such as approximating the di-graph by trimming it) that will be
more thoroughly studied in the future if time, personnel and resources are
available.

2.4.4 Discussion Paper 77-3. One of the major anamolies in queueing
network theory is concerned with feedback phenomena. Discussion Paper 77-3
is a first attempt to explore this feedback in detail to see if networks

with this feature could indeed be simplified to networks without this feature. If such were to be true then network topologies could be simplified and thereby some of the difficulties encountered in Discussion Paper QT 77-2 could be removed. If this could be accomplished then, again, we would hope that computational simplicity would follow at least for the useful Jackson networks. The results of Discussion Paper 77-3 suggest that such simplifications can be made in some cases (e.g., Jackson networks) for some of the network's flow processes (e.g., departure and queue length processes) but one must be careful in interpreting the results (e.g., the outsider and insider see different queue length random processes as shown in this paper). For this reason Discussion Paper QT 77-3 was a partial success and the topic will have to be more fully developed (see also Section 2.1).

2.4.5 Discussion Paper QT 77-4. This paper as well as Discussion Paper QT 77-5 and 6 are a continuum of research efforts into a topic posed by D.C.E.C. personnel. The problems are stated in Discussion Paper QT 77-4 and a theoretic result is advanced to solve them. An investigation was carried out using both the results of this paper as well as the procedures currently employed in the D.C.E.C. simulation. Results of this preliminary investigation for a collection of theoretical networks are given in the paper.

As a follow up to that investigation D.C.E.C. personnel requested several test cases of direct interest to them be compared. Results of these cases are found in Discussion Paper QT 77-5 and QT 77-6. These results were communicated to D.C.E.C. personnel for their use.

2.4.6 Other Topics. Two other topics posed by D.C.E.C. personnel occupied our attention. In [18] it was proposed that we investigate the behavior of queues whose demand process was the superposition of three

other processes called first offered traffic, which could be assumed to be a Poisson process, overflow traffic, which is known to be a renewal process under some conditions, and carried traffic, which is known to be a Markov renewal process in some cases. If these known facts are applicable to the networks considered (we have looked at networks of three cities which are fully connected) then it would be an easy matter to find the superposed process of arrivals to a node. Such results would follow directly and easily from the research in [7].

Unfortunately, these facts are not applicable to the connected networks (networks with alternate routing) since, if for no other reason, the three streams to be superposed are not independent processes. There are no usable results with which we are familiar for the superposition of dependent streams. This result is not surprising since to superpose such streams requires knowing how they are dependent. Even for the simplest networks, this dependency structure has not been investigated (another aspect of this problem is discussed in Section 2.1 where the same problem faces us for superposing the arrival stream and the feedback stream). Research on this problem is continuing therefore. It is an interesting problem that may have significant theoretical as well as applied consequences. For the three city, fully connected network one can find steady state probabilities by complete enumeration of the states, for useful values of channel capacities, by using methods such as those discussed in Section 2.4.3 and probably many others. Such an approach will hardly solve a real problem, however, if for no other reason than that the problems are too big. Therefore one must attempt to deal with enormous digraphs as suggested in Section 2.4.3 or one must attempt to decouple the nodes and therefore face the problems of superposition stated above. Current research on the problem is following this latter path.

Finally, D.C.E.C. personnel have been interested in the problem of overflows from queues. The overflow problem is quite old in the literature of telephone networks and significant research has been done on it. For this reason, the project has served as a consultant to the D.C.E.C. personnel by providing previously published and unpublished papers on the topic, discussions on the problems, and insights gained from previous research by project personnel. It now appears that a D.C.E.C. report will evolve from these efforts.

2.6 <u>Summary</u>. It would appear that research under the contract number given in Section 1.0 has been highly productive. New theoretical results have been obtained and are beginning to be used by others. New applications have been approached with varying degrees of success. For example, the study of queues with deterministic servers, useful for modelling packet-switched computer data networks, is rather far advanced. The study of queues of interconnected servers in voice networks is re-encountered some of the classically hard problems of telephone conjestion theory and progress is slow.

Research personnel has provided a useful service to D.C.E.C. personnel with several types of input to that computer modelling activity. For example, several problems posed have been solved directly through the interaction of the two groups (e.g., see [24]). Other problems posed have produced significant amounts of useful research but more needs to be done (e.g., queueing networks with deterministic servers). Yet other problems posed are proving to be very difficult (e.g., the analysis of connected networks) and considerably more work is needed here to properly solve these problems.

3. <u>Bibliography</u>*

*We include in this list all project reports concluded under the contract

N00014-75-C-0492 (NR042-296). These reports are marked with an asterik(*).

All of these reports (Technical Memoranda) have been distributed to the

names on the mailing list. Discussion Papers are on topics of interest to

D.C.E.C. as discussed in Section 2.4. They have not been distributed to

the entire mailing list. They are denoted as discussion papers herein.

Published papers that have appeared or are in various stages of completion

toward publication that are the direct result of research under this contract

are marked by a double asterik(**). Other references are to work cited in

the body of the report and are not ideas due to our research effort.

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4. Project Personnel Update*
(Including Honors, Awards, etc.)

*Data on personnel has been periodically reported in interim project reports.
The following is an update to those previously given.

Ralph L. Disney, Project Principal Investigator. Professor Disney was
appointed Charles O. Gordon Professor of Industrial Engineering and Operations
Research at the Virginia Polytechnic Institute and State University, Blacksburg,
Virginia. This endowed professorship was bestowed following a national search
for candidates. Professor Disney also received the AЛM (Honorary I.E. Society)
award for outstanding teaching for the 1976-77 academic year from students
in Industrial Engineering at the University of Michigan. Disney chaired one
session and presented a paper in another session at the Seventh Symposium on
Stochastic Processes and their Applications held at Twente University in The
Netherlands, August, 1977. Disney's topic was on queues with feedback. He
will chair a session called Stochastic Mythology at the forthcoming ORSA/TIMS
meeting in Atlanta. He has served, by invitation, on several national committees
for professional societies during the contract period and continues serving on
the S.I.A.M. Visiting Lecturer Program. Professor Disney was invited to give
presentations to Bell Labs, Holmdel and Thomas J. Watson Research Center,
I.B.M. in May 1977 on research work conducted under this contract.

Robert Foley, Research Assistant. Mr. Foley is a Ph.D. candidate in the
Department of Industrial and Operations Engineering at the University of
Michigan. He completed all requirements, except the dissertation, for the
degree in August 1977. Mr. Foley will join Professor Disney at V.P.I. and S.U.
to continue his research work for the degree. He was chosen as one of the six
finalists for the San Francisco ORSA/TIMS Student Paper Competition and

presented a paper on feedback queueing. He will continue in this area and will work on queues with delayed feedback.

Donald C. McNickle, Research Associate. Dr. McNickle served for two years on this research contract. In the first year he was on a Post Doctoral appointment from New Zealand. In the second year he was research associate for the project and devoted the major part of his time to the study of networks with deterministic service times. He has been appointed, at the assistant professor level, to a position in the School of Business, Canterbury University, Christchurch, New Zealand. His duties begin September 1, 1977. While on the project, Dr. McNickle presented papers at both the Las Vegas and Miami ORSA/ TIMS National meetings. His topics were areas associated with his ongoing research with the project. Dr. McNickle was invited to present his results on deterministic server queues to an audience of researchers at the Thomas J. Watson Research Center of I.B.M. in May 1977.

Benjamin Melamed, Research Assistant. Dr. Melamed completed his Ph.D. requirements in the Department of Computers and Communications Sciences at the University of Michigan during the past year. He remained at the University partly supported by funds from the project until August 1977 in order to continue his research on Jackson network simplification and flow in Jackson networks. His Ph.D. dissertation was on these topics. He left the project in August, 1977 to start his work as Assistant Professor in the Department of Industrial and Systems Engineering, Northwestern University. Dr. Melamed presented a paper based on research supported under this contract at the Sixth Symposium on Stochastic Processes and their Applications held at Technion University, Haifa, Israel, in 1976.

Burton Simon, Research Assistant. Mr. Simon is a Ph.D. candidate in the Department of Industrial and Operations Engineering and Mathematics, University

of Michigan. He has been actively involved, most recently, in studies of approximations of flow in queueing networks. Mr. Simon plans to complete his formal requirements for a joint I.E.-Mathematics Ph.D. by December 1977. He will then join Professor Disney at V.P.I. and S.U. to complete his dissertation work on topics of stochastic process approximations.

James Wendel, Research Associate. The project was extremely fortunate to secure the services of Dr. Wendel. Dr. Wendel was a project member for one month in the summer of 1977. Dr. Wendel is a world leader in the theory of probability and random processes. During his time on the project, he served to help direct some of the research of Mr. Foley and Mr. Simon and served as a valuable consultant on most of the topics being researched by other project members.

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