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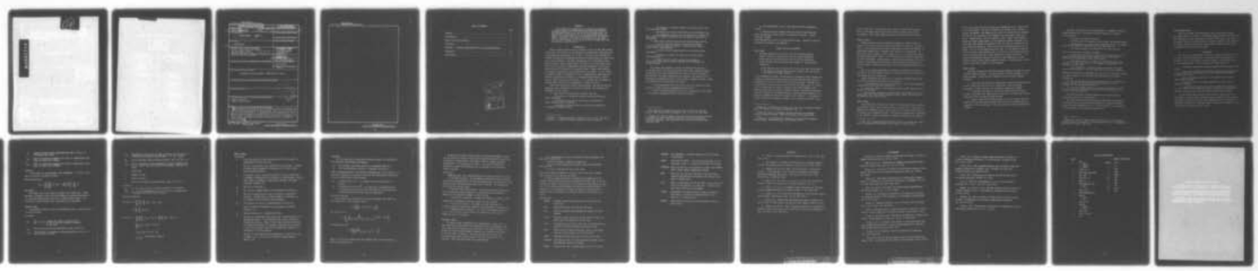

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Four models for studying the file allocation problem in a computer network with distributed data basis were reviewed. Each approach has merit but none is totally satisfactory. An approach which would permit use of all the methods during the design of a network would be of considerable value and could be used to establish a data base, get an estimate of the number of file copies needed, and study the effects of storage and other constraints on file location.

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TABLE OF CONTENTS

ABSTRACT

Four models for studying the file allocation problem in a computer network with distributed data bases were reviewed. Each approach has merit but none is totally satisfactory. An approach which would permit use of all the methods during the design of a network would be of considerable value and could be used to establish a data base, get an estimate of the number of file copies needed, and study the effect of storage and other constraints on file location.

INTRODUCTION

Modern computer/communications technology offers the Navy ADP systems planner many alternatives for satisfying the computational requirements of a geographically distributed set of users. Navy directives require that various alternatives be examined and that the scheme having the lowest life-cycle cost be adopted. The major alternatives to be evaluated in this study included a single large computer serving its users by remote terminals; a set of smaller, independently operated computers; and an interconnected set of computers or a computer network. Among these schemes, the computer networks are the most difficult to evaluate. In this report, a computer network is regarded as a set of geographically separated processors interconnected by means of a communications network to enable data and other resources to be shared. It is assumed that the network is created "from scratch," even though this is rarely the case.

Frank[1] has surveyed the network design problem, and has outlined the important areas in which more research is required. He classifies the problems as of two types:

a) Those that are difficult but tractable, such as

. the analysis of tradeoffs between circuit switching and packet switching,

. the design of routing and flow control techniques for packet switching with priorities,

. the design of networks which are relatively insensitive to changes in network traffic,

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[1] Frank, H., "Computer Networks," Networks, Vol. 5, No. 1, pp. 69-73 (Jan 1975). A complete listing of reports is given on page 19.

. the analysis of tradeoffs between centralized control and distributed data bases,

. the analysis of network survivability and reliability, and

. the realization of realistic cost models that consider the amortization of capital investment, cost of operation, and cost of maintenance.

b) Those whose solutions require major breakthroughs, such as

. a theory which will permit the analysis of dynamic characteristics of a computer network. Current methods usually require static approximations,

. a theory of network measurement for monitoring network performance,

. techniques to permit the prediction of gross network performance, and

. methods that will permit network participants to selectively limit access to their resources (an increasingly important feature).

This report was prepared to assist the ADP Systems planner in evaluating some of the alternatives which arise when tradeoffs between centralized control and distributed data bases are being considered. Specifically, the report summarizes and evaluates four models for determining the optimum location of files within a computer network. These four models may be characterized as follows:

1. Cost minimization with file access time as a constraint, which leads to a linear zero-one programming problem (Chu[2])

2. Access time minimization with cost as a constraint, which leads to an integer programming problem (Chandy and Hewes[3])

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[2] Chu, Wesley W., "Optimal File Allocation in a Multiple Computer System," IEEE Transactions on Computers, Vol. C18, No. 10 (Oct 1969).

[3] Chandy, K.M. and J.E. Hewes, "File Allocation in Distributed Systems," Proceedings of the International Symposium on Computer Performance Modeling, Measurement, and Evaluation (Mar 29-31, 1976) Harvard Univ., Cambridge, Mass.

3. Cost minimization with no constraints solved by enumeration (Casey[4])

4. Various heuristic methods which may involve interaction and which are generally useful only for hierarchical networks. (Casey/Friedman,[5] Chang[6])

Short descriptions of each of these methods follow. Details of the four systems are included in the appendix.

MODELS FOR FILE ALLOCATION

CHU's MODEL

The model described in Chu deals with the following problem:

> "Given a number of computers that process common information files, how can one allocate the files so that the allocation yields minimum overall operating costs subject to the following constraints:
>
> 1) The expected time to access each file is less than a given bound.
> 2) The amount of storage needed at each computer does not exceed the available storage capacity."

In this mathematical model, he describes an information system having a set of nodes of specified storage capacity connected pair-wise with pairs of transmission lines--one for queries and one for replies. Although this interconnection rarely exists in practice and the request rate for a given file by a given node is rarely a constant, Chu's model appears to be realistic--at least for circuit switched networks. Additional assumptions would be necessary for message-switched or packet-switched networks. Chu makes two assumptions which don't appear to be critical: 1) the number of copies of each file is known in advance, and 2) queries are routed to all

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[4] Casey, R.G., "Allocation of Copies of a File in an Information Network," AFIPS 1972 Spring Joint Computer Conference, Vol. 40.

[5] Casey, R.G. and T.D. Friedman, "Design Techniques for Database-Oriented Computer Networks," IBM Research Rept. RJ 1222 (May 1973).

[6] Chang, S.K., "An Interactive Configurator for Distributed Computer System Design," IBM Research Rept. RC 5327 (Mar 1975).

copies of the file. As pointed out by Levin,[7] a network with 30 nodes and 10 files would require about 9000 zero-one variables and 18,000 constraints. Chu's model obviously should not be used for such cases.

CHANDY's MODEL

Chandy considers the file allocation problem at several levels of detail. At the first level of detail, the number of copies of a single file is to be determined, given the frequencies of queries and updates and neglecting storage costs. Average access time is to be minimized. At the second level of detail, total storage cost is a constraint and several different files may be present. At the third level of detail, hierachies are also considered. In this model, a memory is characterized by its cost, capacity, and average retrieval time. The mathematical formulation for the third level of detail was not given in the preliminary version of the paper.

One of the interesting aspects of Chandy's formulation is that, in contrast to all other models studied, the average access time is minimized and storage cost is a constraint.

Chandy formulates the problem as an integer programming problem and notes the following with respect to its solution:

- In 95 percent of the cases, the solution to the linear programming problem satisfies integrality constraints.
- A heuristic based on hill-climbing yielded optimum solutions in 95 percent of the cases.
- The heuristic provides an upper bound on the minimum cost of the system while the linear program provides a lower bound. In 95 percent of the cases the costs are the same.

CASEY's MODEL

Casey describes a mathematical model of an information system having a set of nodes, some of which contain copies of a given file. Each node is assumed to be linked to all the other nodes in the network either directly or possibly via intermediate nodes. Two types of transactions are processed by the network - queries and updates. Queries are assumed to be directed

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[7] Levin, K.D., "Organizing Distributed Data Bases in Computer Net orks," Univ. of Pennsylvania, The Wharton School Report 74-09-01 (1974).

to one copy of the file while updates are transmitted to all copies of the file in the network. The model considers file storage costs, volume of queries and updates, and communications costs for queries and for updates. For most of his discussion, Casey assumes query and update costs to be equal. Communications costs are assumed to vary linearly with distance. Using this rather simple model, the optimization problem considered is to locate the files within the network so that the costs of storage and communications are minimized. Casey derives two interesting results in his paper: 1) If p is the update/query ratio and r is the number of replications of a file in the network, then, if $p \geq 1/(r-1)$, the optimal allocation would be that no more than r nodes should have a copy of the file. 2) A method for finding the optimal allocation is described which is considerably better than a simple exhaustive search. This model will be most useful in the early stages of network design.

CHANG's MODEL

Chang has proposed an extremely detailed mathematical model of a distributed computer network. The model permits a concise statement of the design problem. Chang actually formulates three distributed design problems:

1. Given that processors and communication lines have been sized and located, tasks and files are to be located and a routing strategy determined. Chang calls this the transaction allocation problem.

2. Given that locations of files and processing steps have been assigned, processors and communications lines are to be sized and located. Chang calls this the network design problem.

3. Given a partially specified system, i.e., one in which some processors and lines have been installed and some files allocated, the configuration is to be completed. This Chang calls the system configuration problem.

The major contribution which Chang makes is to suggest a heuristic design procedure for a hierarchical network having the following characteristics:

- Tree-like topological structure
- Several levels of processors with a single top-level processor
- All processors on a given level communicate to the next higher level with full-duplex communications of the same capacity
- All tasks originate and terminate at the same location.

There are three steps in Chang's procedure:

- Transaction allocation, in which the processing steps of the system tasks are allocated to the various levels of the network hierarchy; file allocation is part of this step.
- Processor allocation, in which the processing steps to be performed on a particular level of the network are allocated to the processors on that level.
- Line allocation, in which the exact locations of the processors are determined so that the total line cost can be minimized.

Transaction allocation is performed with the aid of a transaction allocation table supplied by the designer and containing the following information:

(a) For each processor transaction-step pair, the time delay required to process the transaction and the availability of the processor for the transaction are given.

(b) For each communication-line transaction-step pair, the time delay involved in transmitting the step and the availability of the line for the step are given.

The Chang technique considers response time and availability requirements before cost minimization.

In a later paper written by Chang and Tang[8] another technique for allocating files is described which considers the trade-offs between storage cost and transmission cost. It would be useful to incorporate such a technique into the model considered here.

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[8] Chang, S.K. and D.T. Tang, "Processor Allocation in a Distributed Computer System," Proceedings of International Conference on Management of Data, San Jose, Calif. (May 1975).

CASEY/FRIEDMAN MODEL

Casey and Friedman[5] have developed a set of APL functions which they found useful in a study of the network design problem. The functions were designed to permit interactive creation, modification, and evaluation of graphic theoretic representations of computer networks. The properties of computer networks with leased lines as well as dial-up lines may be calculated with the functions provided.

CONCLUSION

Each of the four approaches to the file allocation problem has merit but none is totally satisfactory. An approach which would permit the analyst to use all the methods during the design of the network would be of considerable value. Such a polyalgorithm could be used to

- establish a data base, using the logical structure described by Chandy;
- get a quick estimate of the number of file copies required and an idea of where the local minima in the cost function are located, using Casey's method;
- get an alternative estimate of the number of files copies, using Chandy's method;
- study the effect of storage constraints on file location, using Chu's method;
- consider (when desired) the effect of additional constraints on file location such as those that may be required in a heterogeneous network, using the interactive APL functions described by Casey.[5]

If the network being studied is hierarchical, then the effect of additional constraints may be studied using the heuristics and functions described by Chang.[6] For truly large networks, none of the methods is completely satisfactory, although Chandy's method may be adequate. Casey's enumerative method may prove too costly.

APPENDIX A

DETAILED DESCRIPTIONS OF FILE ALLOCATION MODELS

CHU's MODEL:

Given Data:

a_{ijk}	Expected time for the i^{th} computer to retrieve the j^{th} file from the k^{th} computer
b_i	Storage capacity of i^{th} computer
i	1, 2,...n, where n is the number of computers in the system
j	1, 2,...m, where m is the number of distinct files in the system
l_j	Length of each transaction for j^{th} file
r_j	The number of redundant copies of the j^{th} file
C_{ij}	Storage cost per unit length and unit time of the j^{th} file at the i^{th} computer
C_{ik}	Transmission cost from k^{th} computer to the i^{th} computer per unit length
L_j	Storage required for j^{th} file
P_j	The frequency of modification of the j^{th} file after each transaction
T_{ij}	Maximum allowable average retrieval time for j^{th} file to the i^{th} computer
U_{ij}	Average usage rate of j^{th} file at i^{th} computer

Variables:

X_{ij} = 1 j^{th} file stored in i^{th} computer

= 0, otherwise

Objective Function:

$$\sum_{i,j} C_{ij} L_j X_{ij} + \sum_{i,j,k} C_{ik} L_j U_{ij} X_{kj} (1-X_{ij})$$

Constraints:

1) $\sum_j X_{ij} L_j \leq b_i$ (storage capacity not exceeded)

2) $(1-X_{ij})\, a_{ijk} \leq T_{ij}$ for all j, i=k

(maximum allowable retrieval time not exceeded)

Assumptions:

(1) One pair of transmission paths links each pair of computers; one path for traffic <u>from</u> computer i to computer j and one path for traffic <u>to</u> computer i from computer j.

(2) The expected time for the i^{th} computer to retrieve the j^{th} file from the k^{th} computer i is $a_{ijk} = w_{ik} + w_{ki} + t_{kj}$, where w_{ik} is the expected queuing delay at the i^{th} computer for the channel to the k^{th} computer, w_{ki} is the expected queuing delay at the k^{th} computer for the channel to the i^{th} computer, and t_{kj} is the expected computer acccess time to the j^{th} file. Chu assumes t_{kj} can be neglected.

(3) A file residing on a given computer may be accessed simultaneously by that computer and by a remote computer.

Discussion:

The assumption that the computers in the network are connected pairwise with a pair of transmission paths is rarely if ever true in practice.

CASEY's MODEL

Given Data:

n	Number of nodes
σ_k	Cost (in dollars per month) of storing a copy of the file in question at the k^{th} node
λ_j	Volume of query traffic emanating from node j (j=1,2,...,n) (in megabits per month)

ψ_j Volume of update traffic emanating from node j (j=1,2,...) (in megabits per month)

d_{jk} Costs (in dollars per megabit) of a unit of communication from node j to node k for a query

$\bar{d}_{jk}$ Costs (in dollars per megabit) of a unit of communication from node j to node k for an update

Variables:

I is an index set representing a file assignment. If I(k)=1, then a copy of the file is located at node k.

Objective Function:

$$C(I) = \sum_{j=1}^{n} \left[\sum_{k \epsilon I} \psi_j \, d_{jk} + \lambda_j \min_{k \epsilon I} \bar{d}_{jk} \right] + \sum_{k \epsilon I} \sigma_k$$

Discussion:

This model can be quite useful in spite of its simplicity. Casey describes a parameter study involving finding the optimal allocation for five different update/query ratios for a nineteen-node network. Calculating the optima required only *ten seconds* on an IBM 360/91.

CHANDY's MODEL

This summary considers access time minimization with a cost constraint for multiple files.

Given Data:

d_{jk} $\sum_i r_{ijk} U_{jk}$ Average time spent in updating copy j of file k per unit time due to updates at all sites

q_{jk} Rate at which queries are generated at node j for file k

r_{ijk} Time required to implement an update generated at site i on a copy of file k at site j

t_{ijk}	Response time for a query at node j for file k if the query is satisfied by accessing a copy at node i. If $i=j$, $t_{ijk}=0$
B_{ik}	Cost of storing a copy of file k in site i $k=1....K$, $i=1....N$
C_{ijk}	Cost of replying to a query generated at site j regarding file k, if a copy of the file in site i is accessed to satisfy the query
G	System cost
K	Number of files
N	Number of sites
U	Rate at which updates are generated at node j for file k

Variables:

X_{jk}	=1, if a copy of file k is stored at node j; 0, otherwise
Y_{ijk}	=1, if a query generated at site j for file k is satisfied by accessing a copy of the file at site i.

Objective Function:

Minimize $$\bar{T} = \sum_{i \neq j} \sum_{j} \sum_{k} q_{jk} \cdot U_{ijk} \cdot t_{ijk} + \sum_{j} \sum_{k} d_{jk} x_{jk}$$

Subject to: $$\sum_{i \neq j} \sum_{j} \sum_{k} C_{ijk} \cdot Y_{ijk} + \sum \sum B_{jk} \cdot X_{jk} \leq G$$

$$\sum_{i \neq j} Y_{ijk} + X_{jk} = 1 \text{ all } j,k$$

$$Y_{ijk} \leq X_{jk} \text{ all } i,j,k \quad i \neq j$$

$$Y_{ijk}, X_{jk} \text{ non-negative integers}$$

CHANG's MODEL

Given Data:

A — A set of stations at which processors are to be located; the coordinates of Ai are (Xi, Yi).

π — The set of processors to be installed at the stations. A dummy processor may be assigned to a station if it is not to have any processing capacity.

π_j — A processor π_j has a capacity $\bar{d}_j$ which is a vector containing a parametric representation of capacity of the processor; includes such items as throughput, direct-access storage, and number of terminals attached, etc.

g_j — The cost of processor π_j

σ_j — The cost per thousand bytes of file storage for processor π_j

E — The set of communications lines to be used to interconnect stations. A dummy line e_o of zero capacity is included in E to represent two stations not interconnected.

$\bar{b}_k$ — The capacity of line e_k is represented by the vector $\bar{b}_k$ which contains such parameters as line speed, line buffer capacity, etc.

q_k — The cost per mile of a communication line.

S — The set of transactions (jobs, work load) to be processed by the distributed system. Each transaction may consist of several transaction steps s_i. Each of these steps (1) may be processed at a specified station, (2) requires a specified file (assumed to be at that station), and (3) may require the transmission of information to another station.

D — The set of files required by the transaction. Each file D_i has a length l_i; if it is not to be stored in a mass storage device, l_i=0.

Variables:

Two functions must be found which assign processors to stations and which allocate lines between processors.

ϕ_p The processor allocation function is a mapping from A to π.

ϕ_e The line allocation function is a mapping from AxA to E.

These two mappings specify the hardware configurations of the network. Two additional mappings are required to complete the specification and permit the total system cost to be calculated.

ϕ_S A mapping from s to A. It assigns each transaction step to a station.

ϕ_r A mapping from SxS to 2^{AxA}. For each pair of processing steps, a routing path is specified which describes the path along which information between the two steps is transmitted.

Objective Function:

Total system cost is given as the sum of processor cost, line cost, and storage cost. The processor cost is

$$g = \sum_{\pi_j} \left\{ A_i : d_p \ (A_i) = \pi_j \ g_j \right\}$$

The line cost is:

$$q = \sum_{e_k} \left\{ (Ai_1, Ai_2) \sum : (Ai_1, Ai_2 = e_k) \ q_k ||Ai_1 - Ai_2|| \right\}$$

The storage cost is:

$$\sigma = \sum_{A_i} \left(D \sum : \phi_s \ (S_u) = A_i \ l_u \cdot \sigma_j \right)$$

where σ_j is the file storage cost per thousand bytes for the processor π_j which is allocated to A.

Chang has described a general model for distributed computer systems and has devised a heuristic procedure for generating feasible (satisfying constraints) configurations. The model is far too complex to permit optimization of a function such as cost. A set of APL functions is described to permit experimenting with the procedure for hierarchical computer systems.

Constraints:

Chang describes five constraints which are stated in words as follows:

1. Routing Constraint. The transmission path between two processing steps should originate where the first processing step is located and should terminate where the second processing step is located. The transmission path should not contain loops.

2. Processor Capacity Constraint. The total processing requirements of all transaction steps assigned to a station should not exceed the capacity of the processor assigned to that station.

3. Line Capacity Constraint. Between two stations A_{i_1} and A_{i_2}, the transmission requirement should not exceed the line capacity.

4. Line Slot Constraint. The number of lines connected to a processor should not exceed the number of slots available at the processor.

5. "Compatibility" Constraint. Let II_j be the processor allocated to A'_i. Both the file and the function performed on the file must be compatible with the processor.

FRIEDMAN's MODEL

The network under consideration is represented by a link list. If the network has n nodes which are interconnected by m transmission links, then there will be m entries in the link list. Each entry consists of a unique link identification number followed by the identification numbers of the two nodes it connects. The user provides the link list and identifies which nodes contain copies of the data file which is to be accessed. Other data which must be provided include

• the average amount of query and update activity emanating from each node to each file,

• a table of discrete transmission capacities.

• the cost for maintaining each possible link at each possible capacity, and

• the cost to maintain any file at any node.

With the preceding information, the total cost as the sum of storage and transmission costs may be calculated.

In order to study the effects of changes on the behavior of the network, several APL functions are provided which remove, add, or replace transmission links. No functions for relocating the files among the nodes seem to have been provided although this should be relatively simple. A complete list of functions for leased line networks is given below. A comparable set of functions for a dial-up network is also given in the report.

APL Functions:

FORMCM	Produces connection matrix, given the link list and node count.
OKCM	Determines whether all nodes are connected.
CSP	Looks for shortest path spanning two nodes in a given network.
FILACT	Provides a table containing average amount of query and update activity emanating from each node.
LUACT	Calculates the activity on each link of the network after location of files on network has been specified.
PATH	Finds the set of links connecting a node to the nearest copy of a file located at one or more nodes.
LQACT	Uses PATH to find total query activity on all links.
IARIABLE	Indicates the cost for maintaining each possible link at each possible capacity in network.
FMAINT	Indicates the cost of maintaining any file at any node.

FORMLTAR	Uses TARTABLE to calculate monthly cost of all links (called LTAR).
TARRIF	Uses LTAR and FMAINT to calculate monthly cost of configuration, given the nodes at which files are located.
GETTARRIF	Given the link list and locations of files, calls FORMCM, LQACT, LUACT, MINCAP, FORMCTAR and TARRIF.
SNIP	Using the link list and locations of the file nodes, removes links whenever such removal will result in the same or lowered costs.
JOIN	Adds to a specified node the one link, if any, which will result in the greatest cost reduction. Continues with that node as long as cost decreases.
JOINALL	Accomplishes the same function as JOIN on a network - wide basis. A link will be added anywhere in the network if it reduces costs.
REPLACE	Substitutes new links for old ones whenever this will reduce costs.

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