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Agasaveeran. Saravanan
University of Windsor

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PERFORMANCE EVALUATION OF COMMUNICATION NETWORK IN A CIM SYSTEM - A SIMULATION APPROACH

by

AGASAVEERAN SARAVANAN

A Thesis
submitted to the
Faculty of Graduate Studies and Research
through the Department of
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of the requirements for the Degree
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ABSTRACT

Computer integrated manufacturing is concerned with providing control and high level integrated automation at all levels of manufacturing industries, by linking islands of automation into a distributed processing system. The aim of CIM networking is to provide a means for integration of information flow. Hence, the communication network facility in a CIM system becomes an important resource or facility to be considered while building CIM systems. The available literature on manufacturing systems do not consider this important resource or facility as a factor in the CIM system design process.

Also, CIM networking differs from conventional computer networks as it involves information exchange of both control data as well as less critical non-real time data and internetworking with intercommunication probablities depending on specific manufacturing functions. The focus of this research is to model and analyze the performance of a communication network in a typical computer integrated manufacturing environment.

As the proper operation and functioning of a CIM system

depends on its communication network also, care has to be taken not to overload the system to avoid long delays of messages. At the same time providing overcapacity means high unnecessary costs. So, it is important to find out whether a given network of given capacity is able to perform well for the given inputs. This also helps one, before adding new machines or facilities to the network to determine whether the network can accomodate new communication load brought in by a newly added facility.

The input parameters and the performance metrics of the problem are identified and an example system is chosen to illustrate the modeling and solution methodolgy. Simulation is chosen as a modeling tool and is preferred over analytical models as broadcasting networks have abstract protocols and only simulation model can accomodate them in detail. SLAM II (Simulation Language for Alternative Modeling) is used for modeling because of its capabilities of process and discrete event simulation modeling.

Experimental design techniques are used to study the effect of input factors on system performance. The results are analyzed and 95% confidence intervals are established for each of the performance measures at various levels of

experimental factors. Multiple linear regression model is fitted for predicting the system's response and the predicted values are compared with observed values.

The model was found to be sensitive and followed logical expectations and was verified correct. Complete validation was not possible because of the non-availability of data from a real system to compare with.

Finally, comments are presented regarding practical applicability of the model and the scope for further research.

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To my parents

CHAPTER I

INTRODUCTION

Computer integrated manufacturing is concerned with providing control and high level integrated automation at all levels of manufacturing industries, by linking islands of automation into a distributed processing system. It aims at integration of various functions of manufacturing business including design, manufacturing, sales, finance, purchasing, etc.

Computer Integrated Manufacturing (CIM) systems are basically the evolution of manufacturing systems with information technology integrated into them. The integration of information technology into manufacturing systems leads not only to immediate cost benefits but also better decision support, risk limitation, better cash flow, better inventory management, enhanced customer service and improved quality of working life in the long term. Also this gives improved efficiencies with increased scope of product line.

CIM system integrates many of the advanced manufacturing technologies which remain as the " islands of automation " such as flexible manufacturing systems (FMS), computer aided design and manufacturing (CAD/CAM), and Robotics with the managerial functions to ensure smooth, efficient and effective flow of information avoiding duplication, distortion, etc. Attempts have been made to solve the technical problems of integration by General Motors' manufacturing automation protocol (MAP).

It is clear that integration of information exchange is the key to CIM. This integration of information flow is achieved through the use of computer communication networks. Hence, the communication network facility in a CIM system becomes an important resource or facility to be planned while building CIM systems. The available conventional manufacturing system models do not consider this important resource or facility as a factor in the CIM system design process. So, the focus of this research is to analyze the performance of the communication networks in a typical manufacturing environment.

A brief introduction to CIM systems and its subsystems is given in chapter 2. Chapter 3 introduces computer communication networks and their application to manufacturing environment. A literature review on computer communication networks and their application to manufacturing environment is presented in chapter 4. The objectives of the proposed research are presented in chapter 5. In chapter 6, the problem is formulated; the input parameters, the performance measures are identified and the solution methodolgy is discussed. Also, an example CIM system is presented here which is to be modeled and analyzed. A simulation (SLAM II - Simulation Language for Alternative Modeling) model for performance evaluation of the example system is developed and is given in chapter 7. Also, the verification and validation methodologies of the simulation model are presented.

In chapter 8, the model is analyzed for its performance using experimental design techniques and the results of the analysis are provided. Also, performance prediction regression models are fitted . Chapter 9 provides a detailed discussion on the performance of the system and its significant factors. Recommendations for improvement and the scope for further research are also presented in this chapter.

CHAPTER II

COMPUTER INTEGRATED MANUFACTURING SYSTEMS

2.1 CONCEPT

Computer integrated manufacturing (CIM) system is an integrated system consisting of a business information processing system, a Computer Aided Design (CAD) system, a Computer Aided Manufacturing (CAM) system, a Flexible Manufacturing / Assembly system and an integrating networking system (Ranky, 1986). All the above subsystems have evolved into a high degree of automation in the recent years but unfortunately they remain as the so called "islands of automation" making the management of them difficult. So, efforts are made today towards integration of these islands of automation to achieve a totally integrated automated system which allows free flow of information between the subsystems and sharing of resources. This makes a CIM system extremely flexible and productive with effective utilisation of its resources as the information flow is integrated on a distributed system towards a single goal of the organisation.

2.2 INFORMATION FLOW IN CIM SYSTEMS

2.2.1 IMPORTANCE

The importance of information flow has evolved from the advent of computers. Computers are now used for information processing (note: different from data processing) and chunking of information improves the throughput. As in the CIM environment, there are different functions to be performed by different subsystems it is common to allot dedicated computer workstations to achieve these functions. If a single computer is assigned to do all these duties then the reliability of the system comes down drastically and also the information processing is difficult to manage because of greater variation between the types of information.

As all the subsystems have a single common goal of producing a product, they have to co-ordinate with each other to ensure that the final goal is achieved. This results in a requirement of a lot of interactions between individual stations and hence the information exchange between them.

There are so many instances when exchange of information is required between various equipments and facilities of a CIM system. Some of them are listed below.

1. When a processing information on a part is required.

   e.g. part program by a manufacturing / assembly / inspection workstation from CAD/CAM system.

2. When a workstation requires some aids to process the given information.

   e.g. a machining center may require a tool or fixture from an Automatic Storage and Retrieval System (AS/RS) to process a particular part program to machine a part or it may require adaptive control data (finite element analysis results of vibrations, temperature, cutting forces involved in machining) from the CAD system.

3. Exchange of control data is required

   e.g. Two assembly robots coordinating through the network to make one assembly

4. Dynamic distributed scheduling

   e.g. Networkwide bidding scheme where schedules are made dynamically to allocate a part to a most suitable cell through extensive communication.

5. Status reporting and monitoring of workstations

   e.g regular status reporting by each workstation in the factory regarding its performance to a monitoring workstation

6. Automatic fault diagnosis

   e.g. Information flows when an expert system based fault diagnosis system queries the cell and its elements for breakdowns.

7. Intracell communication

   e.g. To achieve co-ordination between a robot and a machining center while loading / unloading a pallet or fixture, to get feedback from inspection station for subsequent corrective action of the machining center

8. Intercell communication

   e.g. Manufacture of a common part and sharing of resources

9. Production/inventory control

   e.g. CAM system requires information regarding current inventory including work-in-process which has to come from the cell controllers and other stations in the FMS.

10. Traffic control of material handling systems

    e.g. Traffic control of Automated guidance Vechicles (AGVs) require information exchange between the cells, AS/RS and AGV controllers.

There are so many other instances where information exchange is crucial for the proper operation of an automated manufacturing system.

Although the highly automated machines and equipments in a CIM environment are highly reliable still communication failure could occur because of many different reasons related to information exchange as follows:

1. Information required by a particular machine did not reach it at all i.e. information is lost while transmission between two stations because of poor transmission media, etc.

2. Information arrived carries some noise (error) because of external interference, etc.

3. Information required arrives after a critical time period after which it loses its value. This delay depends on the traffic load on the system and how much the system can handle.

So, it is really important to consider information flow along with material flow (includes parts, tools, and fixtures flow) while designing CIM systems. The media which makes this information flow possible thus is an important resource or a facility to be planned so that it could handle the given information load effectively without any problem.

2.2.2 CONSIDERATIONS IN THE DESIGN OF CIM SYSTEMS

There are two major segments of information flow in CIM systems viz. technical and managerial. The technical information integration is concerned with the shop floor level and the managerial information integration is associated with the integration of various managerial functional departments. The major problem is the estimation of the amount of information flow associated with each station because of the unavailability of entropic measures on the messages communicated.

Hence, an easy way of incorporating the information flow considerations in designing CIM systems is to incorporate the physical size of each message measured as the bits/bytes of computer memory storage. Although the physical size does not exactly represent the information content it would suffice for design purposes as the physical media of communication is loaded only with bits or bytes of messages at a particular rate. And it is easy to measure the sizes of the messages in bytes as these data are readily available in the factory network.

Communication networks are described as the media for information exchange. Packet switching mode of operation of communication networks handles messages as packets of restricted sizes. So, the information flow in a CIM system can be accounted for by studying the traffic of packets flow in the communication network. Each station is considered to have certain packet generation rate which follows a certain distribution depending on its communication requirements with the other stations in the same system. The communication network should be capable enough to handle the total packet traffic offered by all the stations in the system. So, a need arises to evaluate the communication network of the CIM system, given the offered traffic load of packets by all stations in the system, for desired measures of performance.

CHAPTER III

COMPUTER COMMUNICATION NETWORKS

3.1 CONCEPT

According to Tanenbaum (1988) a computer network is an interconnected collection of autonomous computers. Two computers are said to be interconnected if they are able to exchange information. The media of communication may be copper wire, lasers, microwaves or communication satellites. The communication subnetwork with the help of interface message processors (IMPs) carries messages from hosts to hosts.

Computer networks are designed in a highly structured manner as a series of layers or levels, each one built upon its predecessor. The purpose of each layer is to offer certain services to the higher layers, shielding those layers from the details of how the offered services are actually implemented. Layer n on one machine carries on a conversation with layer n on another machine. The rules and conventions used in this conversation are collectively known as the layer n protocol. The entities comprising the corresponding layers on different machines are called peer processes. It is the peer processes that communicate using the protocol. The interface between each pair of adjacent layers defines which primitive operations and services the lower layer offers to the upper one. The set of layers and protocols is called the network architecture which is implemented by specific programs and hardware designed for each layer.

International Standards Organization(ISO) has taken steps to standardize various protocols and based on its proposal, OSI(Open Systems Interconnection) reference model is developed which deals with connecting systems that are open for communication with other systems. This seven layer model tells what each layer should do. This model is given in appendix A.

The main goals of networking are resource sharing, providing high reliability by having alternative sources of supply, saving money as small computers have a much better price/performance ratio than large ones, and providing a powerful communication medium among widely separated computers/equipments.

3.2 TYPES

Computer networks are divided into two broad categories based on the physical distance they cover, viz.
A. Local Area Networks(LAN): They cover few kilometers.
B. Wide Area Networks(WAN) : cover thousands of kilometers.

Also, there are two main designs of communication subnetwork based on its mode of operation, viz.

1. Point-to-point network

In this design, IMPs are connected by numerous cables and if two IMPs that do not share a cable want to communicate, they must do this indirectly via. other IMPs. When a message (represented by one or more packets) is sent from one IMP to another via other IMPs, each packet is received at each intermediate IMP in its entirety, stored there until the required output line is free, and then forwarded. Some possible IMP interconnection topologies are Star,Ring and Tree networks.

2. Broadcast network

Here, a single communication channel is shared by all the machines on the network. Packets sent by any machine are received by all the others. An address field within the packet specifies for whom it is intended. Upon receiving a packet, a machine checks the address field and just ignores it if it is intended for some other machine. Some possible broadcast subnets are bus, satellite or radio networks. As a single channel is shared by many machines, a common channel allocation mechanism has to be fixed to resolve collision.

3.3 EXAMPLE NETWORKS

Networks differ in their facilities offered, technical design, and user communities. The facilities available range from arbitrary process to process communication to electronic mail, file transfer, real time control, remote login and remote execution. The technical designs can differ in the transmission media used, the naming and routing algorithms employed, the number and contents of the layers present, and the protocols used. There are many currently operating networks. Some of them are

Public networks (X.25 networks)
ARPANET(Advanced Research Projects Agency NETwork)
MAP (Manufacturing Automation Protocol) and
TOP (Technical and Office Protocols)

CSNET(Computer Science departments' NETwork)
BITNET(Because It's Time NET work)
SNA(Systems Network Architecture)

All of the above use different series of protocol layers and have different standards established for each of these layers. Of the above MAP and TOP are used in a CIM environment and these network architectures are explained below.

3.4 COMPUTER NETWORKS FOR CIM ENVIRONMENT

Local area networks are most suitable for factory floors as their diameters are less than a kilometer. IEEE has published three standards on LAN known as IEEE 802.3 CSMA/CD(Carrier Sense Multiple Access - Collision Detection) based on Ethernet, IEEE 802.4 based on Token bus and IEEE 802.5 based on token ring. All the LANs use packet switching, broadcasting as their mode of transmission. Each packet may be considered as a carrier of information.

In any broadcast network, the main issue is how to determine who gets to use the channel when there is competition for it. Broadcast channels are also called as multiaccess channels or random access channels. The Medium Access Control (MAC) sublayer is important for LANs which use multiaccess channels as the basis of their communication.

Ethernet (IEEE 802.3) works by having all the machines listen to the cable before transmitting. If the cable is idle any machine may transmit. If two machines transmit at the same time there is a collision in which case they all stop, wait for a random period of time and try again later. In theory there is no upper bound on the time a machine might have to wait to send a message.

GM (General Motors), U.S.A. for its assembly line felt it is essential to have the worst case transmission time known in advance(upper bound). So it uses token bus in which machines take turns, round robin,thus giving a deterministic worst case performance rather than a statistical one as in IEEE 802.3 Ethernet or CSMA/CD. IBM has standardised on token ring due to its high reliability and serviceability as well as some other technical advantages.

Token bus (802.4) assumes a linear topology and it can handle different classes of priority messages. It uses 75 ohm broadband co-axial cable and uses three possible different speeds 1, 5, and 10Mbps(Mega bits/sec). Also, baseband cable with 5 Mbps and 10 Mbps can be used. The stations are organized logically into a ring, with each station knowing the address of the station to the left and right. When the logical ring is initialized, the highest numbered station may send the first frame. After it is done, it passes permission to its immediate neighbor by sending the neighbor a special control frame called token. The token propagates around the logical ring, with only the token holder being permitted to transmit frames. Since only one station at a time holds the token, collisions do not occur.

A token bus network is shown in figure 1.

IEEE token ring is not really a broadcast medium but a collection of individual point to point links that happen to form a circle. It runs on twisted pair, coaxial cable or fibre optics and is completely digital. It also has a known upper bound on channel access. The network efficiency can approach 100% under conditions of heavy load. IEEE 802.5 specifically uses shielded twisted pairs running at 1, 2 or 4 Mbps. IEEE 802.5 token ring network is shown in figure 2.

Token ring also has a priority handling scheme but in token ring a station with only low priority may starve to death waiting for a low priority token to appear. In token bus each station gets its fair share of bandwidth.

In IEEE 802.4 the current token holder has special powers. It maintains the logical ring by having a contention interval every cycle. In IEEE 802.5 has a centralized monitor to handle tokens. Both token bus and token ring have excellent throughput and efficiency at high loads.

3.4.1 MAP and TOP

General Motors, U.S.A. has standardised specific protocols in each OSI layer arriving at MAP for factory automation. Boeing has standardised OSI layer protocols calling it TOP which is more suited for office automation. Although MAP and TOF differ at lower level layers at the middle and higher level layers they are compatible. The MAP and TOP protocol suites are shown in figure 3. It may be noted that they follow the OSI model (appendix A) closely.

MAP uses the token bus for the physical medium and TOP uses Ethernet or token ring for its physical medium.

MAP uses a IEEE token bus 802.4 as MAC and TOP uses CSMA/CD 802.3 (Ethernet) and token ring 802.5 as MAC. IEEE 802 LAN standards differ at the physical layer and MAC sublayer but are compatible at the data link layer.

Both MAP and TOP use IEEE 802.2 datalink protocol LLC (Logical Link Control) in the data link layer in the connectionless mode as the service available to the network layer. The LLC sublayer assures timely delivery of real time data by means of following features.

-Acknowledgement and waiver of acknowledgement options

-Right of privileged terminals to transmit a message by interrupting other terminals

-Selective admission of non privileged terminals into the logical ring.

MAP/TOP use ISO 8473, a connectionless networklayer protocol. And the transport layer is ISO 8072/8073 using class 4 connection oriented service. This class assumes that the network layer is not completely reliable and handles all the error control and flow control itself. So it is possible to connect any kind of network no matter how bad it is, to MAP/TOP. But this results in a complex transport layer that must deal with an unreliable network service.

The OSI connection oriented standards ISO 8326/8327 and ISO 8822/8823 are used in MAP and TOP in the session and the presentation layers. Also OSI standards such as file transfer protocol, virtual terminal protocols are used in the application layers.

TOP also recognizes an end system, a repeater, a bridge, a router and a gateway. A repeater just forwards bits from one network to another, making the two networks look logically like one network. A bridge is used to connect two networks at the data link layer particularly when these networks have different data link layers but the same network layer(e.g. a connection between a Ethernet and a token bus). A router is used to connect two networks with the same transport layer but different network layers. A gateway is used to connect to a network that does not use the OSI model at all.

MAP recognizes 6 types of nodes viz. MAP end system, bridge, router, a gateway, the MINIMAP node and MAP/EPA gateway. The last two nodes are compatible to PROWAY LAN standard which was common in factory environments prior to MAP. MAP does not have a repeater - but it uses bridges for that purpose.

3.5 DESIGN OF COMPUTER NETWORKS

The main network design problems are topological design, IMP (Interface massage processor) design and network modeling (Frank, et al., 1972).

The topological design of a network is to achieve a low cost, highly reliable network with a high throughput. The IMP design problem is more concerned about the network operating procedure. IMP design itself has the physical hardware design problem (based on timing and reliability considerations and the operating procedure) and the design and implementation of the operating procedure using the specified IMP hardware. There are four primary areas of operating procedure of the IMP design viz. message handling and buffering, error control, flow control and routing. The IMP provides buffering to handle messages for its host and packets for other IMPs. Error control is required to provide reliable communication of host messages in the presence of noisy communication circuits. The design of the operating procedure should allow high throughput in the network under heavy traffic loads. Two obstacles to achieving this objective are:

1. The network can become congested and cause the throughput to decrease with increasing load, and
2. The routing procedure may be unable to always adapt sufficiently fast to the rapid movement of packets to insure efficient routing. A flow control and routing procedure is needed that can efficiently meet this requirement. Neuman (1989) discusses this problem.

Kurose and Mouftah (1988) describe three general approaches towards network modeling,analysis and design viz.

1. Measurement
2. Analytic techniques
3. Simulation techniques

Measurement techniques provide the most direct means of network performance evaluation; it is also the most expensive one in the sense that a network must first exist (or a prototype constructed) before measurements can be taken. Also it takes a long time to come up with results through experimentation.

Analytic models require a high degree of abstraction and need a lot of efforts to develop a performance model. Also analytic models require that a network to be simple and make a lot of assumptions in modeling a complex network resulting in inaccurate results. Analytic models are most suited for point-to-point networks.

Simulation techniques help to model a network to a greater level of detail and to model complex protocols which are difficult to put in exact analytical form. Computational requirements for simulation are usually large.

As the network in CIM environment is of broadcasting type and different kinds of networks with complex protocols are interconnected together, simulation becomes the most practical tool for performance analysis of communication networks in CIM enviroment.

CHAPTER IV

LITERATURE REVIEW

In this chapter a brief review of literature on the application of computer communication networks for integration of CIM systems is presented.

Manufacturing automation has been evolving from its primitive hardwired automation to the modern softwired automation. The computer revolution has contributed much for this advancement. As the computer systems became more and more sophisticated the level and flexibility of manufacturing automation also improved. Manufacturing automation started with typical hardwired NC machines in 1950's. Then came CNC machines which later evolved into DNC (Direct Numerical Control) systems. Scott, et al. (1983) developed a hierarchial control model for automated manufacturing systems using DNC systems. With the advent of robots and AGVs (Automated Guidance Vechicles) the flexible manufacturing systems were developed. Merchant(1985) defined CIM (Computer Integrated Manufacturing) as the basis for the factory of the future stressing the integration of various manufacturing functions (the so called " islands of automation "). Distributed/intelligent systems were developed for control of automated manufacturing systems. Warnecke, et al. (1987) suggested local area networks for integrating information flow to increase productivity of CIM systems. Patrick (1988) suggested a combined CSMA/CD and token ring factory-wide network as an alternative to an expensive MAP/TOP broadband based network for small industries. His paper also addresses the financial justification of CIM systems.

Much effort has been spent in recent years to standardize a communication networking architecture for CIM environment. This would enable the manufacturers of automation equipments to design their equipments to be compatible with the communication standards. MAP/TOP are such standard protocols now being standardized by GM and Boeing. Local area networks have emerged as powerful media for meeting communication requirements of automated manufacturing environment.

McGuffin, et al. (1988) discuss the distributed computing communication needs of CIM and show how MAP/TOP meets the technical challenges of this environment through their networking architectures. Ilic, et al. (1989) discuss the role of local area networks as a primary communication tool in factory automation as well as the problem of real time control segments. Ray(1988) discusses the challenges involved in the design of CIM network for real time control issues in the manufacturing environment. Pleinevaux and Decotignie (1988) describe the implementation of field buses at the sensory level of manufacturing automation to ensure real time control. Hatfield, et al. (1988) describe the use of fiber optic LANs for the manufacturing environment. Chang, et al. (1988) describe a knowledge based approach for distributed control of a manufacturing cell using MAP network.

Kusiak and Heragu (1988) give a structural perspective of CIM and discuss the impact of machine layout on manufacturing communication. Sintonen and Virvalo(1988) give an experimental framework of a hierarchial communication subsystem consisting of in-cell and in-machine communication networks for solving the distributed communication problems in a programmable assembly cell.

Another important use of communication network in a manufacturing environment is distributed, dynamic scheduling of flexible manufacturing cells. Shaw(1987) describes a distributed scheduling approach that uses the communication network in a CIM environment. This approach is based on a networkwide bid scheme wherein the scheduling decision is made by collecting the price of each manufacturing cell for taking on the job. He also describes a formalism and a model for the distributed scheduling scheme that can be incorporated in a communication protocol.

Shaw(1988) discusses the dynamic scheduling in cellular manufacturing systems using networked decision making. In this paper he describes a method which uses a dynamic, distributed task assignment mechanism executed through a communication network for intercell scheduling and a knowledge based system for cell level scheduling.

Shaw and Whinston (1988) describe the application of distributed artificial intelligence to the real time planning and control of flexible manufacturing systems consisting of asynchronous manufacturing cells. A knowledge based approach is used to determine the course of action, resource sharing, and processor assignments. Within each cell there is an embedded automatic planning system that executes dynamic scheduling and supervises manufacturing operations. Because of the decentralised control, real time task assignments are carried out by a negotiation process among cell hosts through the communication network. The negotiation process is modeled by augmented Petri nets - the combination of production rules and Petri nets - and is executed by a distributed, rule based algorithm.

Ghosh and Wysk(1989) model the performance of communication facilities at each station level with CNC, DNC (Direct Numerical Control) approach. Ghosh and Wysk (1989), compare the application of queueing models, queueing network models and simulation models and predict that simulation models should be used when more accurate information is desired. Queueing models can be used when seeking quick results on the system performance.

Gupta and Ghosh (1989) present a two stage model for joint optimization of production volume and communication system cost for multiproduct manufacturing system.The first stage determines the optimal production volumes and the second stage determines the optimal design parameters for communication system while achieving the near optimal production volumes of the first stage. This paper assumes direct numerical control system rather than distributed control system.

There has been a lot of research going on in the design of computer networks as such in various aspects. Kleinrock (1970) presents analytical and simulation methods involved in computer network design. The main network design problems are topological design, IMP (Interface message processor) design and network performance modeling as discussed in Frank, et al. (1972). Mendiratta and Cornejo (1989) discuss the topological design problem as applied to the virtual circuit based LANs. Gavish and Neuman (1989) discuss the IMP design problem with regard to routing and capacity assignment. Frost, et al. (1988) review the status of efficiency enhancing techniques related to the simulation of computer communication networks.

Bux(1981) provides a comparative evaluation of the local area subnetworks. Metcalfe and Boggs (1976) discuss Ethernet LAN. Liu and Wise (1987) present a performance analysis of a CSMA/CD protocol for local area networks. Lewis(1989) presents measurements on a large Ethernet LAN and its bandwidth utilization. Bux(1989) discusses on token ring LANs and their performance. Strole(1987) gives an overview of the IBM token ring network. Pitt(1987) presents the standards for the IBM token ring. Jayasumana and Fisher (1985) present the token skipping channel access scheme which bypasses idle stations in token bus networks. Colvin and Weaver (1986) discuss the performance of single access classes on the token bus. Clyne (1988) presents an overview of discussions on LAN/WAN interworking. Brady (1988) discusses the performance of an edge-to-edge protocol in a simulated X.25/X.75 packet network.

Strayer and Weaver (1988) study the performance of data transfer services in MAP. Ciminiera, et al. (1988) study the performance of type 3 LLC in industrial 802.5 networks. Marathe and Smith(1988) report an empirical analysis of a MAP network adapter.

Cidon, et al. (1988) model the internal structure of a packet switching node in a real-time system and characterize the tradeoff between throughput, delay, and packet loss as a function of the buffer size, switching speed, etc. They show that with a small number of buffers the node will provide a guaranteed delay bound for high priority traffic, a low average delay for low priority traffic, no loss of packets at the input and low probablity of packet loss at output.

From the above review it is clear that it is very important to evaluate the communication network facility for the given manufacturing system in terms of its meeting the performance requirements. A lacuna is observed in the above literature, namely, none of the papers specifically model a factory based communication network operating in a manufacturing environment where interconnected networks of different types exist and communication between the networks is functionally related.

CHAPTER V

OBJECTIVES OF THIS RESEARCH

The main objective of this research work is to provide a methodology for modeling and performance analysis of communication network in CIM system. The idea is to use the available literature on LANs to model a factory based communication network and to develop a methodology to analyze the model with respect to the system performance parameters.

The important factors to be considered when selecting computer communication networks for CIM system are:

- networking architecture
- protocol
- transmission media used

The chosen communication networking facility should be able to meet the requirements of the given manufacturing environment at a minimum cost. Also it must be flexible enough to accomodate the future changes in the manufacturing system configuration which is very common in a dynamic market environment. Also the need for planning this important facility arises because of the following reasons:

1. To ensure proper flow of information for the smooth operation of the automated manufacturing system without any loss in productivity because of unavailability of required information by any of the automated equipment. The requirements become stringent because of the flow of control data in the network, in a manufacturing environment.
2. To make sure that this networking facility is effectively utilised.
3. To ensure that enough capacity of this facility is available to sustain the offered traffic load.

Given the information about the functional subsystems of CIM and about their communication traffic requirements the first step is to select the networking architecture in general.

Once the general networking architecture is selected the problem now reduces to tuning the networking system with given input parameters to meet some predefined performance metrics. These performance measures differ from system to system depending on their functional requirements. For setting the proper values to the input parameters i.e. to plan the network, a model of the networking system has to be developed and analyzed for sensitivity of performance parameters to the input parameters so that the levels of input parameters which make the system to achieve desired level of performance can be selected. Also, the prediction models for predicting the system performance within the given range of operating parameters have to be developed.

CHAPTER VI

PROBLEM FORMULATION

6.1 INTRODUCTION

As mentioned in the previous chapter, the main aim of this research is to provide a methodology for modeling and performance analysis of communication network in CIM system. In this chapter, the problem inputs and the performance measures are identified and are defined. Also, the solution methodology is presented and a specific CIM system is defined for illustrating the proposed solution methodology.

6.2 PROBLEM INPUTS

The problem inputs have to come from the user of the CIM system. The following information are required from the user:

1. The physical configuration of the manufacturing system.

   This includes the number of workstations and their physical location within the factory.

The workstations may be various manufacturing facilities such as machining centers, assembly robots, inspection stations, AGVs or information processing computers.

2. The functional grouping of workstations and the number of workstations in each group.

   For example, the number of flexible manufacturing cells, flexible assembly cells and the number of stations in each cell, the number of technical and business office workstations available, etc. Technical office workstations include CAD/ CAM workstations, and business office workstations include computer systems performing managerial functions such as finance, marketing and forecasting, etc.

3. Probablities of intergroup and intragroup communication.

   A communication network in the CIM environment has to serve different functional groups which have strong interactions within as well as between them.

   For example, a machining cell(one group) has to communicate with the technical design group(housing CAD/CAM workstations) once in a while to exchange part programs but more frequently within itself.

So, the probablity that a workstation would communicate with any other station in the system depends on its functional interdependency and this has to be estimated by the user. Practically, this depends on the number of partfamilies and the complexity of manufacturing features of each part family. A complex part may require processing in more than one cell, calling for intercell communication.

4. The communication traffic load offered by the system.

The offered communication traffic load has two components viz. arrival rate and the message length. It is measured by bits/sec. It may be noted that the total offered traffic load is the sum of all products of average packet generation rate and average message length of individual workstations. Also the distribution followed by arrival rate and message length must be known. These data could be obtained from the past records and measurements of these parameters in the factory through empirical studies.

At this point it may be noted that the traffic load has nothing to do with the information processing load within each station as communication network does the function of transferring information only.

5. Network configuration/Protocol

As such the user is not left with much choice regarding the type of network to be used. But the particular configuration of network which fits the physical system is important for modeling.

MAP/TOP architecture is more suited for integration of manufacturing system as discussed in earlier chapters. MAP uses IEEE token bus and TOP uses IEEE token ring. There are a number of token bus and token ring subnetworks in the factory environment connecting specific groups of machines, computers, etc. which are again interconnected by a factory based backbone network. The interconnection of networks requires bridges or gateways which become important resources to be shared by a number of stations. So, the number of subnetworks and the associated number of bridges and gateways become important input parameters.

6. Network operating parameters

There are a number of network hardware operating parameters which are to be fixed before any further analysis. Each subnetwork follows its own protocol and requires some hardware inputs. For example, token passing time and response window size are important in the case of token bus network.

The choice of transmission media may be copper wire (baseband or broadband) or fiber optics. The bandwidth of media used (data transmission rate in Mbits/sec) in the links of the subnets and the physical lengths of communication links form part of the problem inputs.

6.3 PERFORMANCE MEASURES

The performance measures reflect the requirements of the end system which is the CIM system. There are three important performance measures viz.

1. System packet delay
2. System throughput
3. Scantime

Each of the above performance parameters are explained in detail below.

6.3.1 SYSTEM PACKET DELAY

All the stations (computers or controllers) in a CIM communication network communicate with each other by sending information as packets. The packets are delayed in the system before they reach their destination due to many reasons depending on the states of the system they have to go through. Very late arrival of these packets may affect the total cycle time of the product and hence the productivity of the manufacturing system as the machines may remain idle waiting for information. As an example, consider a machining center which has requested a part program from the CAM system. If the arrival of this information is delayed the productive machine hours are wasted accordingly as the machine can not act further without the part program; further if this operation is in the critical path it would affect the completion time of the product. So, the average time a packet spends in the system is a performance measure of the system.

6.3.2 SYSTEM THROUGHPUT

Throughput of the system is nothing but the average transmission rate of data bits through the system. This gives a measure of utilisation of the networking system as it represents the fraction of time the network is used to transmit data packets. As the networking facility involves costs, providing extra capacity above what is actually required to service the offered traffic result in underutilised, suboptimal systems. So, it is important to have the network throughput as a performance measure while designing the system. As the network has so many subnetworks it is difficult to estabilish an expression for overall utilisation. Individual subnetworks' utilisation and throughputs may be evaluated separately and analyzed if required.

6.3.3 SCANTIME

As mentioned earlier, CIM system environment requires exchange of both very critical control data and less critical non-real time data.

Example of a system where control data traffic is critical is a typical robotic assembly cell or line where one or more robots in combination perform an assembly operation on a unit. This usually requires coordination of one or more robots necessiting communication of control data through the communication network. So, the network has to respond within a critical time period making the exchange of control data meaningful. The control data loses its value after the elapse of this critical time period. So the network response time for control data traffic is a primary performance measure. As the assembly cells and manufacturing cells are connected by token bus networks, the cycle time or scantime of the token is a measure of network response in control applications. This is defined as the time taken by the token between two consecutive arrivals at the same station. Scantime can be used to evaluate the utilisation of the network. The ratio of the average message service time to the scan time is the utilisation of the network.

6.4 PROBLEM OUTPUTS

The problem outputs would be to determine the effects of input factors on the performance measures and to estabilish their significance levels. Based on this the prediction models for system performance are also estabilished.

6.5 PROPOSED SOLUTION METHODOLOGY

The proposed solution methodology is to model the given interconnected token ring and token bus networks using simulation methods. The analytical techniques such as queueing theory to model these broadcasting networks have to make some simplifying assumptions to make the models less complex as the protocols are abstract in nature. Simulation models can model these abstract protocols to a greater detail and are expected to be more accurate. Moreover, as the problem requires modeling of interconnected networks with different operating parameters, servicing messages of different sizes, which arrive at different probablities, simulation is more suitable since various features of a message can be taken care of by means of atributes. In this research, discrete event simulation techniques would be applied to model the given networking system.

6.6 AN EXAMPLE CIM SYSTEM

An example of a CIM system has to be taken to discuss the solution methodology in detail and more specifically. This example system is shown in fig 4. The factory consists of four main functional subgroups viz. technical planning, shopfloor management, flexible machining cell and flexible assembly cell. Technical planning group has CAD, CAM and Business workstations connected by a token ring network(Ring M). Shop floor management group has AS/RS control station, Monitoring, and Material handling control stations connected by a token ring network (Ring N). Flexible machining cell has a machining center, a robot, a cell manager station and an inspection station connected by a token bus network(Bus U). Flexible assembly cell has two assembly robots, an inspection/testing station and a cell manager station (Bus V).

The intercommunication probablities are assumed to be known and are shown in Appendix B. These probablities were not completely chosen randomly but rather by the functional relationships among the stations and different networks. As mentioned earlier these have to be estabilished by the user by empirical research.

There are five network submodules viz. ring1, ring2, bus1, bus2 and backbone as well as two interconneting interfaces viz. full duplex cable and bridge. The full duplex cable is one which allows two way communication simultaneously. This cable is selected at a higher data rate to enhance data transmission between networks.

The input parameters are initially assumed as follows:

Network protocols used: IEEE 802.4 Token bus
IEEE 802.5 Token ring

The backbone network assumed is Token bus with broadband cable(10 Mbps); only one channel is used for data transfer.

The average network diameter is 1000 metres.

All the token bus subnets use 5 or 10 Mbps base band cable and all the token ring subnets use 2 or 4 Mbps coaxial cable (base band) as media of transmission.

There are 2 classes of priorities of messages low (1) and high(2).

Mean token passing time = 10 micro secs for ring nets.
Mean token passing time = 83.5 micro secs for bus nets.
Mean token passing time =50 micro secs for backbone bus nets

Signal speed on the bus = 2*E+08 m/sec
Length of full duplex cable = 400m.
Data transfer rate by full duplex cable = 10 Mbps

Token length in ring nets = 48 bits(over head)
Packet overhead in token bus = 184 bits
Round trip delay(Ring) = 5 microsecs

Propagation delay (Bus) = 5 microsecs

Time delay per medium access unit = 1 micro sec

Deterministic bridge processing time = 200 micro secs.

Response window size = 125 micro secs.

Mean message length of low priority messages: 2 KBytes

Mean interarrival time of low priority messages: 100 milli seconds.

Mean message length of high priority messages: 0.25, 0.5 KBytes.

Mean message interarrival time of high priority messages: 10, 5 milli secs.

The low priority messages are assumed to be generated only by business w/s, CAD and CAM w/s and the business w/s does not generate any high priority messages. The rest of the stations generate high priority messages.

6.6.1 LIST OF ASSUMPTIONS:

The following are the assumptions made for developing the simulation model of the system.

1. All the input message generation/arrival rates follow Poisson process.

2. All the packet sizes are assumed to follow exponential distribution.

3. All the buffers are assumed to hold a capacity of maximum of 100 messages.

4. At any time not more than 800 messages are allowed to be present in the system. This assumption is made to avoid congestion in the system and the delays increasing indefinitely.

CHAPTER VII

SIMULATION MODEL

7.1 INTRODUCTION

The development of discrete event simulation model of the given interconnected network is discussed in this chapter. As the interconnected network has both token ring and token bus networks, first both protocols are described in detail before modeling is attempted. The simulation model was developed using SLAM II(PC version). The discrete event model was possible because all the state variables that describe the system such as number of packets in the system, number of busy stations in the system, etc. change at discrete points in time. The process oriented approach suggested by Pritsker(1986) is employed for modeling the system.

The model has five major modules, one for each network ring1, ring2, bus1, bus2 and backbone. Each module has three major submodules viz. message generation, network service, and token synchronization. Furthermore, each module does the functions of collecting internetwork traffic, routing and collection of statistics.

The model is highly flexible for change as it is completely modular and structured.

7.2 COMMUNICATION PROTOCOLS USED IN THE MODEL

Before getting into modeling the exact mode of service provided by the networks have to be known. So, this section explains in detail how the token ring and token bus protocols work.

7.2.1 TOKEN RING PROTOCOL

The control mechanism for regulating data flow in a ring topology is based on the principle that permission to use the communications link is passed sequentially from node to node around the ring. With the token access control scheme, a single token circulates around the ring (fig. 2), giving each node, in turn, an opportunity to transmit data when it receives the token. A node having data to transmit can capture the token, change the token status to indicate a frame, and begin data transmission. The data to be transmitted is attached with the busy token and transmitted. The node that initiates a frame transfer must remove that frame from the ring and issue a new free token upon receipt of the frame it transmitted. If a node finishes transmitting the entire frame prior to receiving the header of its own frame, it continues to transmit idle characters(contiguous 0-bits) until the header is recognized. This ensures that only one token or frame is on the ring at any time.

The token access control protocol provides uniform access to the ring for all nodes. A node must release a token after each transmission and is not allowed to transmit continuously on a single token. All other nodes on the ring will have a chance to capture a token before that node can capture the token again. The priority mode and reservation indicators in the token frame are used to control the priority access to the tokens. The high priority level messages always get the preference for next transmission.

Normal token operation is insured by a token monitor function that is always active on each ring. This is primarily for maintaining the ring-seeing that token is not lost, taking action when the ring breaks(discontinuity), cleaning the ring up when garbled frames appear, and watching out for orphan frames(frames claimed by no station). Every active station has the capability of becoming the monitor.

There is a delay involved in passing the token from one station to another which can not be utilised at all. Also as each message transmission requires busy token to be attached to it, there is a constant framing overhead for every transmission. Further there is a one bit delay involved at the interface between the station and the ring. All these delays have to be accounted for while modeling and analysis.

7.2.2 TOKEN BUS PROTOCOL

As dicussed earlier, the token bus forms a logical ring during its operation. When the ring is initialized, stations are inserted into it in order of station address, from highest to lowest. Token passing is also done from high to low addresses. Each time a station acquires the token, it must maintain a record of its active successor in the ring and pass the token on to it.

Adding new stations and removing the inactive stations to and from the logical ring are done maintaining the known worst case bound on token rotation. Here, unlike the token ring the monitoring function is totally decentralized. The current token holder has special powers and it keeps track of addition and deletion of stations to/from the logical ring. Periodically, the token holder solicits bids from the stations not currently in the ring that wish to join by sending a SOLICIT_SUCCESSOR frame. The frame gives the sender's address and the successor's address. Stations inside that range may bid to enter. If no station bids to enter within a specified response time, the response window is closed and the current token holder continues with its normal business. Token bus also can handle limited number of priority classes of messages. Apart from the token passing time as in the case of token ring there is an additional delay involved in maintaining the logical ring (= response window size) and this has to be incorporated in the model.

7.3 SIMULATION MODEL

SLAM II simulation language is selected for modeling purposes because of its capabilities and easy availability. The different phases of message transmission are represented as discrete events. Network modeling technique is employed.

The system modeling includes the modeling of traffic sources connected to the LANs, modeling of the procedural characteristics of a particular access method (protocol) and modeling of the data flows in the network configuration or topology. Here we assume finite buffer sizes at each station which allow a maximum of 100 messages to be queued for transmission. First in first out service policy is followed with queues which are always ranked by priorities.

Any message which is generated at a station in the system may require service from one or more networks. The service time of a message depends on its length and the data transfer rate of the current network and is given by,

$$\text{Service time} = \frac{\text{The message length(bits)}}{\text{The data transfer rate of the current network(bits/sec)}}$$

There is also a constant delay involved in the transmission medium because of the limitations of signal propagation speed(2-6 micro secs. normally). The messages queue up at each station depending on their arrival rate. As messages are served by a token, which can be considered as a cyclic server, the cycle time (difference in time between subsequent arrivals of token at the same station)varies each cycle depending on the queues of messages and the individual message lengths. And as only one message per station is serviced during each cycle any new message coming into the queue has to wait till the messages ahead of it in its own queue complete their service and a random amount of time depending on the server availability which in turn depend on the traffic in other queues as well as their message length distributions. And the fact that in a system of interconnected networks networks of different capacities exist, which changes the basic service time of a message itself(length/data rate) as the message flows through the system, makes it very complex to model the situation analytically. A simulation model to model this situation has been attempted and is found to be successful. The simulation program using SLAM II for the example network is given in Appendix B. The list of SLAM variables and atributes used in the program are defined below.

SLAM II VARIABLES

XX(1)-Mean interarrival time of low priority messages in milli secs.

XX(2)-Mean interarrival time of high priority messages in milli secs.

XX(3)-Mean message length of low priority messages in bytes

XX(4)-Mean message length of high priority messages in bytes

XX(5)-XX(8),XX(18) - Used in scantime evaluation

XX(9)-Bridge processing time-200 micro secs.

XX(10)-Channel bandwidth for ring networks in Megabits / millisecs.

XX(11)-Channel bandwidth for bus networks in Megabits/ millisecs.

XX(12)-Channel bandwidth for backbone bus:5E3 Mbits/msec

XX(13)-XX(17) Service time for the current message in networks M,N,U,V, and X

SLAM II ATRIBUTES

ATRIB(1)-1,2: Priority levels Low,High (used as GATE no. in token synchronization network)

ATRIB(2)-Time of creation (Used as scan time in token sync.)

ATRIB(3)-Resource number

ATRIB(4)-GATE number

ATRIB(5)-1,2,3,4: Destination network - M,N,U,V

ATRIB(6) - A sample from given message length distribution

ATRIB(7)-ATRIB(11)- used in token synchronization routines;

7.3.1 TOKEN RING MODULE

Figure 5 shows the SLAM network model for a token ring network which is serving the technical design group of workstations. The creation of messages is done according to the given problem inputs. XX(1) is a SLAM variable which represents mean interarrival time of low priority messages with mean message length of XX(3) bytes. Similarly, XX(2) and XX(4) represent the mean interarrival time and mean message lengths of high priority messages. Each message has an atribute ATRIB(2) for interarrival time and ATRIB(6) for message lengths. ATRIB(1) represents the priority class to which the message belongs. ATRIB(5) gives the address of destination network to which a particular message may be routed to depending on the probablity of intercommunication.

Each station is modeled as a resource of capacity one since a station can not start the next transmission until the current one is complete. Each message in the queue seizes its resource before it is transmitted and frees the resource once its service is complete. So, all the arriving messages at different stations await their respective resources in respective queues. Once a message gets hold of its resource(station) and is ready to be transmitted it still has to wait for the free token which is circulating in the network to arrive at the interface between station and the network. Each interface is modeled as one gate which is opened only once in a cycle for 1 micro sec duration to allow a message to seize the token . To get hold of token the message waits in another AWAIT node for the gate to open in its respective file number. The token circulation is synchronized by passing the current service time values through specific variables(XX(13) in the case of Ring1) and maintaining its circulation indefinitely in a disjoint network, and also by taking care of the token passing time(0.010 millisecs. in the case of ring1) and one bit interface delay. So, the token synchronisation network, in a way pulses the flow of messages in the main network. Once the message gets the token then it takes exactly, (message length + overhead)/channel data rate + propagation delay to complete its service(represented by XX(13)). After completion the atribute of the message is checked for its destination. If it is the current network then its statistics are collected and it is terminated. Otherwise it is routed to its destination address through full duplex cable. This full duplex cable can also be considered as a single server in either direction and is represented as a queue in either direction. Its service time is given by (propagation delay + data transmission time).

If the message has to go to the other kind of network (token bus) it has to cross the bridge and it has to undergo a service in the backbone network module.

Also it may be noted that the current network may have to serve the internetwork traffic apart from the intra network traffic created. Messages from some other networks again wait for their respective resources and gates to get serviced in this network. Their service time may be determined without any problem as they carry their personal data as atributes.

7.3.2 TOKEN BUS MODULE

This is different from the ring module mainly in the token synchronisation section as it operates as a logical ring. This incorporates the fact that inactive stations are removed from the ring thus resulting in removal of their quota of total token passing time around the network. Also there is a constant delay involved at the end of every cycle for maintaining the logical ring of size equal to response window. This is taken care of by adding a delay activity at the end of every cycle. This module is presented in fig. 6. It may be noted that here we have high priority traffic which is true since it is a manufacturing environment.

7.3.3 BACKBONE BUS MODULE

This has a similar token bus module except that there are no message creations in this module i.e. input to this module comes from different networks. This module does the job of routing the traffic between token ring and token bus type of networks. Also the hardware operating parameters of the backbone token bus are different. Only one data channel of backbone bus is assumed to be used and there is only one cyclic server in this module. This module is shown in fig. 7.

The bridge processing time of XX(9) [0.2 msecs] is experienced by each message coming into the backbone module and leaving the backbone module. Also, messages have to wait in queues for bridge service. The bridge processing time includes conversion of the frame formats between different types of networks as well as routing. The backbone network comes in between the bridges.

The performance measures such as throughput and average delay in the system, scan time(cycle time) are collected within each network as well as in a overall manner.

7.4 MODEL VERIFICATION AND VALIDATION

Verification is determining whether a simulation model performs as intended i.e. debugging a computer program. (Law and Kelton, 1982). As the program is modular each module was tested individually whether it gives desired result. Also, for known results the model's inputs were framed and tested with reference to the results expected to be achieved. For example, intercommunication packet routing was checked by assigning various values for the probablities of intercommunication between 0 to 1 for a specific subnetwork and studying that network's output statistics. The "trace" option in SLAM II was used to check the critical sections of the program such as token synchronisation, whether current service time variables were assigned proper values by transfer. The program behaved positively for all the above tests and the model was verified as correct.

Validation is determining whether a simulation model (as opposed to computer program) is an accurate representation of the real world system under study. In the case of a CIM system the real world system performance results for similar inputs were extremely difficult to obtain to make comparison with the simulation output. Hence, the general suggested validation procedure of comparing the simulation model outputs with that of the real system was not possible. However, efforts have been taken to validate the model through sensitivity analysis. From Tanenbaum (1988), the efficiency of token ring and token bus protocols increase as the input traffic load increases. Measuring the efficiency as throughput, throughput was found to increase as the input traffic load was increased. Also, delay was found to increase as the load on the system was increased keeping the data rate of the networks constant. This is true since a message has to wait longer for the token when traffic is heavy i.e. all stations in the network have non-empty queues. Thus, the model responds as per the basic logical expectations and hence is considered valid with respect to the communication network used.

CHAPTER VIII

MODEL ANALYSIS AND RESULTS

8.1 INTRODUCTION

Having finalised the model it is important to analyze the behaviour of the system through the model. In this chapter, the effects of input factors on the system performance are estabilished. There are a number of input parameters available and to do detailed analysis for all of them is really expensive as most of the factors may not be significant. So, the important input parameters are first identified and their effects on the performance metrics of the system are estimated along with their significance levels through an experimental design and subsequent analysis.

8.2 EXPERIMENTAL DESIGN

Several preliminary runs are made at finalising the input parameters which would affect the system performance the most. The network hardware operating parameters such as token passing time and response window size are fixed as constant as the given network configuration is fixed. The important parameters to which the model is sensitive are found to be the offered traffic load and the data rate of networks. Offered traffic load is nothing but total bits/sec created at all stations in the network. This has two components viz. mean message length (XX(4)) and mean message interarrival time (XX(2)). The data rate of both bus (XX(11)) as well as ring (XX(10)) networks were found to have considerable effect on the system. So, the input parameters or factors to be studied are mean message length, mean interarrival time, ring data rate and bus data rate. The performance metrics as discussed earlier are average system packet delay and average throughput of the system. Scan time of assembly cell network, utilisation of assembly cell network and throughput of assembly cell network are included as performance measures so that the effects of factors on assembly cell subnetwork could be demonstrated.

A 2^4-factorial experimental design is developed and it is presented in Table 1. The two levels of each factor and the experimental combinations are also given. The levels are chosen to represent the near extremal conditions of the system. Only the channel capacities are controllable factors

TABLE 1

2^4 - FACTORIAL EXPERIMENTAL DESIGN

	FACTORS			
	* D	C	B	A
EXPT.NO.	XX(2)	XX(4)	XX(11)	XX(10)
1.	0	0	0	0
2.	0	0	0	1
3.	0	0	1	0
4.	0	0	1	1
5.	0	1	0	0
6.	0	1	0	1
7.	0	1	1	0
8.	0	1	1	1
9.	1	0	0	0
10.	1	0	0	1
11.	1	0	1	0
12.	1	0	1	1
13.	1	1	0	0
14.	1	1	0	1
15.	1	1	1	0
16.	1	1	1	1

LEVELS	XX(2) msec	XX(4) bytes	XX(11) Mbits/ms	XX(10) Mbits/ms
0	10	250	5E3	2E3
1	5	500	10E3	4E3

* A: Data rate of token ring network - Mbits/ms

B: Data rate of token bus network - Mbits/ms

C: Mean message length of high priority messages-bytes

D: Mean interarrival time of high priority messages-ms in a real system. But it is always in the interest of the user to find out the system response if the input load is increased. All the values of performance measures were obtained for each of these experimental conditions by running the simulation program. The output statistics are collected for the service completion of 500 messages after allowing 50 millisecs of initial warm up period. Terminating simulation is followed here since it is enough to study the network during the peak period(i.e.peak arrival traffic). As in terminating simulation the initial conditions may affect the output considerably, the warm up period has to be provided for each simulation run to allow the system to evolve to a state of peak period before actually starting to collect statistics (Law and Kelton, 1982).

Now for each experiment 90% confidence levels on mean values of the performance measures were established using the fixed sample size procedure (Law and Kelton, 1982) with 10 replications by changing seed values of random number streams used for simulation. The mean values along with their maximum absolute precision values are given in Table 2. To establish these absolute precision levels 10 replications were sufficient enough. This procedure is very important to minimize the randomness of the output. The

TABLE 2

MEAN VALUES OF PERFORMANCE PARAMETERS*

EXPT. NO. **	SYSTEM DELAY (±15) ms	SYSTEM THROUGHPUT (±0.9) Mbps	ASSEM. NET SCANTIME 4 (±0.08) ms	ASNET UTIL4 (±1.7) %	ASNET TPUT (±0.3) Mbps
1.	145	6.49	0.473	10.14	2.03
2.	152	6.02	0.413	9.69	1.96
3.	157	5.62	0.338	8.58	1.57
4.	150	5.91	0.433	9.79	1.93
5.	145	5.262	0.359	8.77	1.64
6.	143	5.35	0.348	8.76	1.65
7.	152	5.470	0.372	9.11	1.67
8.	144	5.242	0.346	8.72	1.65
9.	161	5.233	0.459	10.22	1.91
10.	158	4.592	0.305	7.93	1.43
11.	151	5.803	0.349	8.74	1.47
12.	153	5.506	0.481	10.5	1.97
13.	208	6.59	5.66	15.14	2.83
14.	188	6.13	3.127	10.52	2.09
15.	140	5.61	0.359	8.91	1.54
16.	153	5.3	0.35	8.77	1.7

* All the above results are established after 10 replications of each experiment.

** The maximum absolute precision values obtained at 90% confidence level.

variance reduction technique of using antithetic variates as suggested by Law and Kelton(1982) was employed to obtain greater precision (smaller confidence intervals) for the same amount of replications.

Care was taken to keep the " environment " the same between different experiments. This is to ensure that the same sequence of random numbers that are generated are used for same purposes between experiments. This was achieved by generating all the random elements related to an entity at the time of creation of that entity itself and storing them as atributes of that entity. For example, the message length of an entity was created in the creation module itself and stored in ATRIB(6) of that entity before that entity started flowing through the system. This atribute value is later used in the system to calculate the service time as the entity flows through various service modules of the system. The TRACE option in SLAM was used to verify whether the evaluation of these random sampling functions is done at the ASSIGN nodes placed in the message creation module itself and it was found to be true.

8.3 ANALYSIS OF EFFECTS OF FACTORS

The analysis of the simulation outputs (Table 2) for the experimental design was done to estimate the effects of each factor on the performance measures. The results of the analysis are presented Tables 3 through 7. The estimates of the factor effects multiplied by half form the co-efficients of a linear regression model representing the response variable as the sum of the variables of main effects and interaction effects (Law and Kelton, 1982). So, these estimates could be used for predicting the system performance. For example, the regression model for system packet delay would be as follows:

$$\text{System Packet Delay} = 156.25 + (-2.25/2) * x_{A} + (-12.5/2)*x_{B} + (5.75/2)*x_{C} + (15.5/2)*x_{D} + (2.25/2)*x_{AB} + (-/2)*x_{AC} + (0.25/2)*x_{AD} + (-11.25/2)*x_{BC} + (-17/2)*x_{BD} + (4.5/2)*x_{ABC} + (7.25/2)*x_{ABD} + (0.5/2)*x_{ACD} + (10.75/2)*x_{CD} + (-10.75/2)*x_{BCD} + (2.5/2)*x_{ABCD}$$

This model has a quite a number of parameters and is clumsy. Most of the factor effects may not be significant at all. So, to determine which factors are significant the normal probablity plots for each performance measure are plotted and are given in Figures 8 through 12 to show the level of significance of each factor effect graphically. From this important factors are identified and multiple regression models are fitted only with respect to these factors. For example, the fitted regression model for system packet delay is presented in Table 16 and is plotted against the observed values in Figure 14. Multifactor ANOVA was performed to evaluate the significance level of effects of each factor and are given in Tables 8 through 15. Also, the 95% confidence intervals were estabilished for various levels of main as well as interaction factors upto 2-levels and are provided in the Tables 8 through 15.

CHAPTER IX

DISCUSSION AND CONCLUSIONS

9.1 INTRODUCTION

In the previous chapter, the experimental factors which have significant effects on the system performance were identified and their effects and significance levels were evaluated. Also, 95% confidence intervals for the system's response were estabilished for different levels of the factors as well as regression model were fitted to predict the system's performance. In this chapter, a thorough discussion on the results is presented and ways of improving system's performance are also given.

9.2 DISCUSSION

The significant factors which affect the system packet delay were found to be interaction factor between token bus data rate and arrival traffic and arrival traffic (From Table 3, Fig. 8, Table 16 & Fig 14 - BCD,CD,BD). The arrival traffic(CD) is combination of message length and arrival rate. The ring data rate is not very significant because most of the data traffic is generated in token bus type of network. BCD has negative effects on delay which implies that the increase in bus capacity results in higher decrease in delay than the increase offered by increase in offered traffic at the decided levels. So, the solution to reduce system packet delay is to increase the bus capacity but this results in additional costs. The arrival rate is usually uncontrollable. As the interaction effect of arrival traffic (CD) has positive coefficient increase in the arrival traffic would increase the delay which is expected. Also, the interaction factor between the token bus capacity and arrival rate (BD) is significant as the increase in arrival rate results in increase in queue length and more load on the system. The confidence levels for the system packet delay for different levels of BD are given in Fig. 13 and from Table 9 it can be concluded that the bus capacity of 5Mbps and the interarrival time of 10 ms would result in minimum system packet delay for the given operating conditions.

The most important factor which affects the system throughput(average data bits transmitted/sec) is the traffic rate (CD) i.e. interactions effects due to message length and interarrival time (Table 4, Fig. 9). The network overall throughput should increase as the input data traffic is increased and that is perfectly reflected by the model. It may be noted that smaller message lengths result in larger token overheads than the larger message lengths for the same arrival traffic rate. Also, it may be noted that when the traffic rate is not very high then, higher arrival rate means that a message has lesser residual waiting time for a token. Also, the system throughput can not be increased indefinitely by increasing arrival traffic as the communication network has finite capacity.

From Table 12 and Fig 10 it may be noted that the scan time of the assembly cell network is mostly affected by factors CD and BCD, the offered traffic rate and its interaction with bus capacity. From Table 13 we find that higher the bus capacity and lower the traffic rate, lower the scan time. At the same time utilisation of same network is also affected by bus capacity-arrival rate and ring-bus capacity (BCD and AB from Table 6, Fig. 11), but higher the capacity, lower the utilisation(-ve effect) and higher the traffic rate, higher the utilisation (CD effect is positive). Increase in ring capacity (data rate) when interacting with bus capacity gives higher utilisation as intercommunication flow is improved by increasing ring capacity and hence more long messages(reduced token overhead) may go to bus network improving utilisation. Increasing utilisation of the network also increases scan time and hence degrade the network response for the given data rate of network which in turn, may endanger assembly robots'coordination, communicating through this particular network. So, a compromise has to be made between these two. Also, the throughput of the assembly cell network can be found to be directly proportional to assembly cell network's utilisation (average service time/average scan time) by comparing Fig. 12 with Fig 11. This is true since the throughput (average number of data bits transmitted per sec) is only a fraction of utilisation by the amount of token overhead used in data transmission.

From the above discussions clearly emerge two critical significant factors which affect the system performance the arrival traffic and its interaction with bus capacity. These have serious physical interpretations. For example, one could not add more machines or facilities to a manufacturing cell or assembly cell without affecting the system performance. If the system is already operating under critical conditions, even an addition of a single machine would increase the communication load and hence the system may completely collapse. Also, providing overcapacity of network as precautionary measures would result in higher costs. Hence, it is important to do an analysis of the system as presented in this research before any physical modifications are made. Also, a need arises to incorporate this important aspect in the model for planning or designing any computer automated manufacturing system for its sucessful implementation.

9.3 CONCLUSIONS

The problem objectives as proposed in chapter 5, have been achieved. The example system was sucessfully modeled and a detailed analysis on it was provided. Although the system chosen was more specific, the methodology is quite general. Any CIM communication network can be modeled and analyzed using the methodology presented in this research.

The concept of simulation as applied to communication network modeling is proven to be an accurate, effective tool for analysis. Although analytical models can be developed with simplifying assumptions, they fail to serve the purpose where most of the assumptions made become impractical. The validation of simulation model with regard to the communication protocols was done using sensitivity analysis, but the model's output was not compared to that of a real CIM system's output because of non-availability of data. The model was found to be sensitive with respect to given inputs and it followed the logical expectations. Any change in the system can be easily accomodated in the model because of the modular nature of the model. SLAM II language was chosen because of its capability to perform process and discrete event simulation and its availability. Any simulation language which has discrete event simulation capabilities can be used for this type of modeling.

The network protocols used in developing this model are the latest ones and are adopted by presently developing automated manufacturing firms. However, new updations have to be incorporated in the model then and there to keep the model uptodate.

There is a scope for further research in connection to this area. How to relate the input traffic distributions to the parts being manufactured in the factory is an important problem to be solved. This has to be solved empirically by analyzing day-to-day data from the factory.

However the model developed in this research is still applicable. If the input distributions follow a distribution other than exponential, the new distribution has to be introduced in the message generation section. In the situation where message generation does not follow any readily available distribution exactly the user is advised to fit an empirical distribution (Law and Kelton, 1982) and introduce it in the model. This model when applied to real systems could easily predict whether the required performance criteria are met such as average system packet delay is well within the limits or scan time is above the sampling period of the communicating controllers or the system has too much of capacity then required i.e. very little utilisation.

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APPENDIX A

THE OSI REFERENCE MODEL

OSI (Open Systems Interconnection) reference model developed by International Standards Organization(ISO) is discussed below. This seven layer model tells what each layer should do. This is not a network architecture as it does not specify the exact services and protocols to be used in each layer.

The physical layer is concerned with transmitting raw bits over a communication channel. The design issues here deal with mechanical, electrical, and procedural interfaces, and the physical transmission medium, which lies below the physical layer.

Tha data link layer's task is to take a raw transmission facility and transform into a line that appears free of transmission errors to the network layer by having the sender break the input data up into data frames, transmit the frames sequentially, and process the acknowledgement frames sent back by the receiver. Physical layer merely transmits a stream of bits without any regard to the meaning of frame structure. Further data link layer has to perform the task of error handling and flow control between IMPs (to keep the fast transmitter from drowning a slow receiver in data). Also data link layer has to handle the traffic of acknowledgement frames.

The network layer is concerned with controlling the operation of the subnet. The design issues of this layer are routing (static or dynamic) of packets from source to destination, congestion control, accounting of packets sent by each source, and interconnection of heterogeneous networks.

The transport layer has to accept data from the session layer, split it up into smaller units , pass these to the network layer, and ensure that the pieces all arrive correctly at the other end. It determines what type of service to provide the session layer viz. an error free point-to-point channel or broadcasting of messages to multiple destinations. This layer is a true end-to-end layer as a program on the source machine carries on conversation with a similar program on the destination machine, using the message headers and control messages. In lower layers the protocols are between each machine and its neighbours(IMPs). Also, transport layer must regulate the flow of information between the hosts.

The session layer allows users on different machines to establish sessions between them. A session might be used to allow a user to log into a remote time-sharing system or to transfer a file between two machines. Session layer's services include managing dialogue control between two hosts and synchronization in case of large file transfers with in between system crashes.

The presentation layer is concerned with the syntax and semantics of information transmitted rather than just moving the bits reliably from here and there. It manages the abstract data structures and conversion from their representation inside the computer to the network standard representation. It also handles data compression and cryptography.

The application layer contains a variety of protocols that are commonly needed. It has all the virtual terminal software to support many different terminal types which work on the network. Also it handles transfer of files between two incompatible systems. Further it handles electronic mail, remote job entry, directory lookup, and various other general purpose and special purpose facilities.

The data transmission in the OSI model occurs as follows. The sending process has some data it wants to send to the receiving process. It gives the data to the application layer, which then attaches the application header to the front of it and gives the resulting item to the presentation layer. The presentation layer may transform this item and add a header to the front , giving the result to the session layer. The process is repeated until the data reach the physical layer where they are actually transmitted to the receiving machine. On that machine the various headers are stripped off one by one as the message propagates up the layers until it finally arrives at the receiving process. There are two major types of services used by the layers as below.

1. connection-oriented service which is like a telephone

system. The service user first establishes a connection, uses the connection and then terminates the connection.

2. connectionless service which is like a postal system. Each message carries the full destination address and each one is routed through the system independent of all the others. Unacknowledged connectionless service is called datagram service.

APPENDIX B

```
;*********SIMULATION MODEL OF FACTORY NETWORK************


;The factory consists of four main functional groups viz.
;Technical planning, Shopfloor management, Flexible
;machining cell and flexible assembly cell.

;Technical planning group has CAD,CAM and Business
;workstations connected by a token ring network - Ring1

;Shop floor management group has AS/R system, Monitoring,
;and Material handling workstations connected by a token
;ring network - Ring2

;Flexible machining cell has a machining center, a robot, a
;cell manager and a inspection station connected by a token
;bus network - bus1

;Flexible assembly cell has two assembly robots, a
;inspection/testing station and a cell manager station-bus2

;This program contains five network submodules viz. ring1,
;ring2, bus1, bus2 and backbone as well as two
;interconneting interfaces viz. full duplex cable and bridge


;SLAM II VARIABLES


;XX(1)-MEAN INTERARRIVAL TIME OF LOW PRIORITY MESSAGES IN
;MILLI SECONDS.

;XX(2)-MEAN INTERARRIVAL TIME OF HIGH PRIORITY MESSAGES IN
;MILLI SECS.

;XX(3)-MEAN MESSAGE LENGTH OF LOW PRIORITY MESSAGES IN BYTES

;XX(4)-MEAN MESSAGE LENGTH OF HIGH PRIORITY MESSAGES IN
;BYTES

;XX(5)-XX(8),XX(18) - USED IN SCAN TIME ESTIMATION
```

```
;XX(9)-BRIDGE PROCESSING TIME: 200 MICRO SECS.

;PROPAGATION DELAY IN FULL DUPLEX CABLES-0.002 MILLI SECS.
;FOR AN AVERAGE DISTANCE OF 400M AND PROPAGATION SPEED OF
;2 * E+08 M/SEC.

;XX(10)-CHANNEL BANDWIDTH FOR RING NETWORKS IN MEGABITS /
;MILLISECS.

;XX(11)- CHANNEL BANDWIDTH FOR BUS NETWORKS IN
;MEGABITS/MILLI SECS.

;XX(12)- CHANNEL BANDWIDTH FOR BACKBONE BUS: 5E3 MBITS/msec

;MEAN TOKEN PASSING TIME BET. TWO STATIONS IN TOKEN RING
;NETWORKS  0.010 MILLISECS

;MEAN TOKEN PASSING TIME BETWEEN TWO STATIONS IN TOKEN BUS
;NETWORKS 0.0835 MILLI SECS

;MEAN TOKEN PASSING TIME BETWEEN TWO STATIONS IN BACKBONE
;TOKEN BUS NETWORK 0.050 MILLISECS

;RESPONSE WINDOW SIZE IN TOKEN BUS 0.125 MILLI SECS

;ROUND TRIP PROPAGATION DELAY IN RING (1000M) - 0.005 msecs.

;PROPAGATION DELAY IN BUS (1000M) 0.005 MILLI SECS.

;XX(13)-XX(17) SERVICE TIME FOR THE CURRENT MESSAGE IN
;NETWORKS M,N,U,V, AND X


;SLAM II ATRIBUTES


;ATRIB(1)-1,2: PRIORITY LEVELS LOW,HIGH (USED AS GATE NO. IN
;TOKEN SYNCHRONIZATION NETWORK)

;ATRIB(2)-TIME OF CREATION (USED AS SCAN TIME IN TOKEN SYNC)

;ATRIB(3)-RESOURCE NUMBER

;ATRIB(4)-GATE NUMBER
```

```
;ATRIB(5)-1,2,3,4: DESTINATION NETWORK - M,N,U,V

;ATRIB(6) - A SAMPLE FROM GIVEN MESSAGE LENGTH DISTRIBUTION

;ATRIB(7)-ATRIB(11) - FOR TOKEN SYNCHRONIZATION;


;**************** SLAM NETWORK PROGRAM ***************



GEN,SARA,CIM FACTORY NETWORKS, 08/03/89,16;

LIMITS,60,7,800;

SEEDS,3324611/Y;

PRIORITY/1,HVF(1)/2,HVF(1)/3,HVF(1)/4,HVF(1);
PRIORITY/5,HVF(1)/6,HVF(1);
PRIORITY/7,HVF(1)/8,HVF(1)/9,HVF(1);
PRIORITY/10,HVF(1)/11,HVF(1)/12,LVF(1);
PRIORITY/13,HVF(1)/14,HVF(1)/15,HVF(1);
PRIORITY/16,HVF(1)/17,HVF(1)/18,HVF(1);
PRIORITY/19,HVF(1)/20,HVF(1)/21,HVF(1);
PRIORITY/22,HVF(1)/23,HVF(1)/24,HVF(1);
PRIORITY/49,HVF(1)/50,HVF(1)/51,HVF(1);
PRIORITY/52,HVF(1)/53,HVF(1)/54,HVF(1);
PRIORITY/55,HVF(1)/56,HVF(1)/57,HVF(1)/58,HVF(1);

INTLC,XX(1)=100,XX(3)=2000,XX(9)=0.200,XX(12)=10E3;
INTLC,XX(2)=10,XX(4)=250,XX(11)=5E3,XX(10)=2E3;EXPT. 1

NETWORK;

;RESOURCE BLOCK

        RESOURCE/M1,1/M2,2/M3,3/M4,4/M5,5;
        RESOURCE/N1,6/N2,7/N3,8/N4,9/N5,10;
        RESOURCE/U1,11/U2,12/U3,13/U4,14/U5,15/U6,16;
        RESOURCE/V1,17/V2,18/V3,19/V4,20/V5,21/V6,22;
        RESOURCE/X1,23/X2,24;

;GATE BLOCK

        GATE/MI1,CLOSE,25/MI2,CLOSE,26/MI3,CLOSE,27;
```

```
        GATE/MI4,CLOSE,28;
        GATE/MI5,CLOSE,29;
        GATE/NI1,CLOSE,30/NI2,CLOSE,31/NI3,CLOSE,32;
        GATE/NI4,CLOSE,33;
        GATE/NI5,CLOSE,34/UI1,CLOSE,35/UI2,CLOSE,36;
        GATE/UI3,CLOSE,37/UI4,CLOSE,38/UI5,CLOSE,39;
        GATE/UI6,CLOSE,40;
        GATE/VI1,CLOSE,41/VI2,CLOSE,42/VI3,CLOSE,43;
        GATE/VI4,CLOSE,44;
        GATE/VI5,CLOSE,45/VI6,CLOSE,46/XI1,CLOSE,47;
        GATE/XI2,CLOSE,48;

;      TECHNICAL PLANNING GROUP

;              R1:    TOKEN RING MODULE 1 - 3 STATIONS

;                     INTRA NETWORK TRAFFIC

;     STATION 1 - BUSINESS INFORMATION PROCESSING WORKSTATION

        CREATE,EXPON(XX(1)),,2;
 G1     GOON,1;
        ACT,,0.8,P1;
        ACT,,0.2,P2;
        ACT,,0.0,P3;
        ACT,,0.0,P4;
 P1     ASSIGN,ATRIB(5)=1,1;
        ACT,,,G2;
 P2     ASSIGN,ATRIB(5)=2,1;
        ACT,,,G2;
 P3     ASSIGN,ATRIB(5)=3,1;
        ACT,,,G2;
 P4     ASSIGN,ATRIB(5)=4,1;
        ACT,,,G2
 G2     GOON,1;
        ASSIGN,ATRIB(1)=1,ATRIB(3)=1,ATRIB(4)=25;
        ASSIGN,ATRIB(6)=EXPON(XX(3)),1;
        ACT,,,QUE;

 ;      STATION 2 - CAD WORKSTATION

 ;      LOW PRIORITY TRAFFIC

         CREATE,EXPON(XX(1)),,2;
```

```
 G3     GOON,1;
        ACT,,0.8,P5;
        ACT,,0.10,P6;
        ACT,,0.05,P7;
        ACT,,0.05,P8;
 P5     ASSIGN,ATRIB(5)=1,1;
        ACT,,,G4;
 P6     ASSIGN,ATRIB(5)=2,1;
        ACT,,,G4;
 P7     ASSIGN,ATRIB(5)=3,1;
        ACT,,,G4;
 P8     ASSIGN,ATRIB(5)=4,1;
        ACT,,,G4
 G4     GOON,1;
        ASSIGN,ATRIB(1)=1,ATRIB(3)=2,ATRIB(4)=26;
        ASSIGN,ATRIB(6)=EXPON(XX(3)),1;
        ACT,,,QUE;

;      CAD WORKSTATION - HIGH PRIORITY TRAFFIC

        CREATE,EXPON(XX(2)),,2;
 G5     GOON,1;
        ACT,,0.15,P9;
        ACT,,0.10,P10;
        ACT,,0.5,P11;
        ACT,,0.25,P12;
 P9     ASSIGN,ATRIB(5)=1,1;
        ACT,,,G6;
 P10    ASSIGN,ATRIB(5)=2,1;
        ACT,,,G6;
 P11    ASSIGN,ATRIB(5)=3,1;
        ACT,,,G6;
 P12    ASSIGN,ATRIB(5)=4,1;
        ACT,,,G6;
 G6     GOON,1;
        ASSIGN,ATRIB(1)=2,ATRIB(3)=2,ATRIB(4)=26;
        ASSIGN,ATRIB(6)=EXPON(XX(4)),1;
        ACT,,,QUE;

;      STATION 3 - CAM WORKSTATION

;      LOW PRIORITY TRAFFIC

        CREATE,EXPON(XX(1)),,2;
 G7     GOON,1;
        ACT,,0.6,P13;
```

```
       ACT,,0.10,P14;
       ACT,,0.15,P15;
       ACT,,0.15,P16;
P13    ASSIGN,ATRIB(5)=1,1;
       ACT,,,G8;
P14    ASSIGN,ATRIB(5)=2,1;
       ACT,,,G8;
P15    ASSIGN,ATRIB(5)=3,1;
       ACT,,,G8;
P16    ASSIGN,ATRIB(5)=4,1;
       ACT,,,G8;
G8     GOON,1;
       ASSIGN,ATRIB(1)=1,ATRIB(3)=3,ATRIB(4)=27;
       ASSIGN,ATRIB(6)=EXPON(XX(3)),1;
       ACT,,,QUE;


;      CAM WORKSTATION - HIGH PRIORITY TRAFFIC

       CREATE,EXPON(XX(2)),,2;
G9     GOON,1;
       ACT,,0.05,P17;
       ACT,,0.15,P18;
       ACT,,0.4,P19;
       ACT,,0.4,P20;
P17    ASSIGN,ATRIB(5)=1,1;
       ACT,,,G10;
P18    ASSIGN,ATRIB(5)=2,1;
       ACT,,,G10;
P19    ASSIGN,ATRIB(5)=3,1;
       ACT,,,G10;
P20    ASSIGN,ATRIB(5)=4,1;
       ACT,,,G10;
G10    GOON,1;
       ASSIGN,ATRIB(1)=2,ATRIB(3)=3,ATRIB(4)=27;
       ASSIGN,ATRIB(6)=EXPON(XX(4)),1;
       ACT,,,QUE;

;      INTERNETWORK TRAFFIC

NMR    ASSIGN,ATRIB(3)=4,ATRIB(4)=28;
       ACT,,,QUE;
B1MR   ASSIGN,ATRIB(3)=5,ATRIB(4)=29;
       ACT,,,QUE;
```

```
;        CHANNEL CYCLIC (GATED) SERVICE

QUE     AWAIT(ATRIB(3)=1,5/100),ATRIB(3)/1;
        AWAIT(ATRIB(4)=25,29),ATRIB(3);
        ASSIGN,XX(13)=8*ATRIB(6)/XX(10)+48/XX(10)+0.006;
        ACT,XX(13);
        FREE,ATRIB(3);
        ACT,0.01;
        ASSIGN,XX(13)=0;SET THE CURRENT SERVICE TIME = 0
        GOON,1;
        ACT,,ATRIB(5).EQ.1,TIS1;
        ACT,,ATRIB(5).EQ.2,MNT;
        ACT,,ATRIB(5).GT.2,MB1T;

;      COLLECT STATISTICS ON PACKETS ADDRESSED TO THIS NETWORK

TIS1    COLCT,INT(2),PKT DELAY1,,1;
        COLCT,BET,TIME BET. ARR1,,1;
        COLCT,ATRIB(6),PKT LEN1,,1;
        ACT,,,TIS;

;       ROUTE PACKETS TO OTHER NETWORKS

MNT     QUEUE(49),,100;
        ACT,0.002+8*ATRIB(6)/XX(12),,MNR;Rec. buf. N
MB1T    QUEUE(50),,100;
        ACT,0.002+8*ATRIB(6)/XX(12),,RB1R;Rec. buf. B1

;       SHOPFLOOR MANAGEMENT GROUP

;       R2:     TOKEN RING MODULE2 - 3 STATIONS

;       STATION1 - AS/R SYSTEM WORKSTATION

        CREATE,EXPON(XX(2)),,2;
K1      GOON,1;
        ACT,,0.3,R1;
        ACT,,0.10,R2;
        ACT,,0.3,R3;
        ACT,,0.3,R4;
R1      ASSIGN,ATRIB(5)=2,1;
        ACT,,,K2;
R2      ASSIGN,ATRIB(5)=1,1;
        ACT,,,K2;
R3      ASSIGN,ATRIB(5)=3,1;
        ACT,,,K2;
```

```
R4      ASSIGN,ATRIB(5)=4,1;
        ACT,,,K2
K2      GOON,1;
        ASSIGN,ATRIB(1)=2,ATRIB(3)=6,ATRIB(4)=30;
        ASSIGN,ATRIB(6)=EXPON(XX(4)),1;
        ACT,,,QU;

;       STATION 2 - MONITORING STATION

        CREATE,EXPON(XX(2)),,2;
K3      GOON,1;
        ACT,,0.2,R5;
        ACT,,0.1,R6;
        ACT,,0.35,R7;
        ACT,,0.35,R8;
R5      ASSIGN,ATRIB(5)=2,1;
        ACT,,,K4;
R6      ASSIGN,ATRIB(5)=1,1;
        ACT,,,K4;
R7      ASSIGN,ATRIB(5)=3,1;
        ACT,,,K4;
R8      ASSIGN,ATRIB(5)=4,1;
        ACT,,,K4;
K4      GOON,1;
        ASSIGN,ATRIB(1)=2,ATRIB(3)=7,ATRIB(4)=31;
        ASSIGN,ATRIB(6)=EXPON(XX(4)),1;
        ACT,,,QU;

;       STATION 3 - MATERIAL HANDLING

        CREATE,EXPON(XX(2)),,2;
K5      GOON,1;
        ACT,,0.3,R9;
        ACT,,0.1,R10;
        ACT,,0.3,R11;
        ACT,,0.3,R12;
R9      ASSIGN,ATRIB(5)=2,1;
        ACT,,,K6;
R10     ASSIGN,ATRIB(5)=1,1;
        ACT,,,K6;
R11     ASSIGN,ATRIB(5)=3,1;
        ACT,,,K6;
R12     ASSIGN,ATRIB(5)=4,1;
        ACT,,,K6;
K6      GOON,1;
        ASSIGN,ATRIB(1)=2,ATRIB(3)=8,ATRIB(4)=32;
```

```
        ASSIGN,ATRIB(6)=EXPON(XX(4)),1;
        ACT,,,QU;

;       INTER NETWORK TRAFFIC

MNR     ASSIGN,ATRIB(3)=9,ATRIB(4)=33;
        ACT,,,QU;
B1NR    ASSIGN,ATRIB(3)=10,ATRIB(4)=34;
        ACT,,,QU;

;       RING2 CYCLIC SERVICE

QU      AWAIT(ATRIB(3)=6,10/100),ATRIB(3)/1;
        AWAIT(ATRIB(4)=30,34),ATRIB(3);
        ASSIGN,XX(14)=8*ATRIB(6)/XX(10)+48/XX(10)+0.006;
        ACT,XX(14);
        FREE,ATRIB(3);
        ACT,0.01;
        ASSIGN,XX(14)=0;SET THE CURRENT SERVICE TIME = 0
        GOON,1;
        ACT,,ATRIB(5).EQ.2,TIS2;
        ACT,,ATRIB(5).EQ.1,NMT;
        ACT,,ATRIB(5).GT.2,NB1T;

;       COLLECT STATISTICS ON PACKETS DESTINED TO RING2

TIS2    COLCT,INT(2),PKT DELAY2,,1;
        COLCT,BET,TIME BET. ARR2,,1;
        COLCT,ATRIB(6),PKT LEN2,,1;
        ACT,,,TIS;

;       SEND INTERNETWORK TRAFFIC TO TRANSMITTER QUEUES

NMT     QUEUE(51),,100;
        ACT,0.002+8*ATRIB(6)/XX(12),,NMR;Rec. buf. R1
NB1T    QUEUE(52),,100;
        ACT,0.002+8*ATRIB(6)/XX(12),,RB1R;Rec. buf. B1

;       FLEXIBLE MANUFACTURING CELL
;       U1:     TOKEN BUS MODULE 1 - 4 STATIONS
;       STATION 1 - MACHINING CENTER

        CREATE,EXPON(XX(2)),,2;
I1      GOON,1;
        ACT,,0.45,S1;
        ACT,,0.05,S2;
```

```
        ACT,,0.2,S3;
        ACT,,0.3,S4;
S1      ASSIGN,ATRIB(5)=3,1;
        ACT,,,I2;
S2      ASSIGN,ATRIB(5)=4,1;
        ACT,,,I2;
S3      ASSIGN,ATRIB(5)=1,1;
        ACT,,,I2;
S4      ASSIGN,ATRIB(5)=2,1;
        ACT,,,I2
I2      GOON,1;
        ASSIGN,ATRIB(1)=2,ATRIB(3)=11, ATRIB(4)=35;
        ASSIGN,ATRIB(6)=EXPON(XX(4)),1;
        ACT,,,Q;

;       STATION 2 - ROBOT


        CREATE,EXPON(XX(2)),,2;
I3      GOON,1;
        ACT,,0.45,S5;
        ACT,,0.05,S6;
        ACT,,0.2,S7;
        ACT,,0.3,S8;
S5      ASSIGN,ATRIB(5)=3,1;
        ACT,,,I4;
S6      ASSIGN,ATRIB(5)=4,1;
        ACT,,,I4;
S7      ASSIGN,ATRIB(5)=1,1;
        ACT,,,I4;
S8      ASSIGN,ATRIB(5)=2,1;
        ACT,,,I4
I4      GOON,1;
        ASSIGN,ATRIB(1)=2,ATRIB(3)=12,ATRIB(4)=36;
        ASSIGN,ATRIB(6)=EXPON(XX(4)),1;
        ACT,,,Q;

;       STATION 3 - INSPECTION STATION

        CREATE,EXPON(XX(2)),,2;
I5      GOON,1;
        ACT,,0.45,S9;
        ACT,,0.15,S10;
        ACT,,0.15,S11;
        ACT,,0.25,S12;
S9      ASSIGN,ATRIB(5)=3,1;
```

```
        ACT,,,I6;
S10     ASSIGN,ATRIB(5)=4,1;
        ACT,,,I6;
S11     ASSIGN,ATRIB(5)=1,1;
        ACT,,,I6;
S12     ASSIGN,ATRIB(5)=2,1;
        ACT,,,I6;
I6      GOON,1;
        ASSIGN,ATRIB(1)=2,ATRIB(3)=13,ATRIB(4)=37;
        ASSIGN,ATRIB(6)=EXPON(XX(4)),1;
        ACT,,,Q;

;       STATION 4 - CELL SUPERVISOR

        CREATE,EXPON(XX(2)),,2;
I7      GOON,1;
        ACT,,0.45,S13;
        ACT,,0.15,S14;
        ACT,,0.2,S15;
        ACT,,0.2,S16;
S13     ASSIGN,ATRIB(5)=3,1;
        ACT,,,I8;
S14     ASSIGN,ATRIB(5)=4,1;
        ACT,,,I8;
S15     ASSIGN,ATRIB(5)=1,1;
        ACT,,,I8;
S16     ASSIGN,ATRIB(5)=2,1;
        ACT,,,I8;
I8      GOON,1;
        ASSIGN,ATRIB(1)=2,ATRIB(3)=14,ATRIB(4)=38;
        ASSIGN,ATRIB(6)=EXPON(XX(4)),1;
        ACT,,,Q;

;       INTERNETWORK TRAFFIC

VUR     ASSIGN,ATRIB(3)=15,ATRIB(4)=39;
        ACT,,,Q;
B2UR    ASSIGN,ATRIB(3)=16,ATRIB(4)=40;
        ACT,,,Q;

;       CYCLIC SERVICE (LOGICAL RING)

Q       AWAIT(ATRIB(3)=11,16/100),ATRIB(3)/1;
        AWAIT(ATRIB(4)=35,40),ATRIB(3);
        ASSIGN,XX(15)=8*ATRIB(6)/XX(11)+184/XX(11)+0.006;
        ACT,XX(15);
```

```
      FREE,ATRIB(3);
      ACT,0.0835;
      ASSIGN,XX(15)=0;SET THE CURRENT SERVICE TIME = 0
      GOON,1;
      ACT,,ATRIB(5).EQ.3,TIS3;
      ACT,,ATRIB(5).EQ.4,UVT;
      ACT,,ATRIB(5).LT.3,UB2T;

;     COLLECT STATISTICS ON PACKETS ADDRESSED TO U1

TIS3  COLCT,INT(2),PKT DELAY3,,1;
      COLCT,BET,TIME BET. ARR3,,1;
      COLCT,ATRIB(6),PKT LEN3,,1;
      ACT,,,TIS;


UVT   QUEUE(53),,100;
      ACT,0.002+8*ATRIB(6)/XX(12),,UVR;Rec. buf.4
UB2T  QUEUE(54),,100;
      ACT,0.002+8*ATRIB(6)/XX(12),,KB2R;Rec. buf. B1

;     FLEXIBLE ASSEMBLY CELL

;     U2:    TOKEN BUS MODULE 2 - 4 STATIONS

;     STATION 1 - ROBOT1


      CREATE,EXPON(XX(2)),,2;
J1    GOON,1;
      ACT,,0.6,T1;
      ACT,,0.01,T2;
      ACT,,0.19,T3;
      ACT,,0.2,T4;
T1    ASSIGN,ATRIB(5)=4,1;
      ACT,,,J2;
T2    ASSIGN,ATRIB(5)=3,1;
      ACT,,,J2;
T3    ASSIGN,ATRIB(5)=1,1;
      ACT,,,J2;
T4    ASSIGN,ATRIB(5)=2,1;
      ACT,,,J2
J2    GOON,1;
      ASSIGN,ATRIB(1)=2,ATRIB(3)=17,ATRIB(4)=41;
      ASSIGN,ATRIB(6)=EXPON(XX(4)),1;
      ACT,,,QQ;
```

```
;       STATION 2 - ROBOT2

        CREATE,EXPON(XX(2)),,2;
J3      GOON,1;
        ACT,,0.6,T5;
        ACT,,0.01,T6;
        ACT,,0.19,T7;
        ACT,,0.2,T8;
T5      ASSIGN,ATRIB(5)=4,1;
        ACT,,,J4;
T6      ASSIGN,ATRIB(5)=3,1;
        ACT,,,J4;
T7      ASSIGN,ATRIB(5)=1,1;
        ACT,,,J4;
T8      ASSIGN,ATRIB(5)=2,1;
        ACT,,,J4
J4      GOON,1;
        ASSIGN,ATRIB(1)=2,ATRIB(3)=18,ATRIB(4)=42;
        ASSIGN,ATRIB(6)=EXPON(XX(4)),1;
        ACT,,,QQ;


;       STATION 3 - INSPECTION STATION

        CREATE,EXPON(XX(2)),,2;
J5      GOON,1;
        ACT,,0.45,T9;
        ACT,,0.15,T10;
        ACT,,0.15,T11;
        ACT,,0.25,T12;
T9      ASSIGN,ATRIB(5)=4,1;
        ACT,,,J6;
T10     ASSIGN,ATRIB(5)=3,1;
        ACT,,,J6;
T11     ASSIGN,ATRIB(5)=1,1;
        ACT,,,J6;
T12     ASSIGN,ATRIB(5)=2,1;
        ACT,,,J6;
J6      GOON,1;
        ASSIGN,ATRIB(1)=2,ATRIB(3)=19,ATRIB(4)=43;
        ASSIGN,ATRIB(6)=EXPON(XX(4)),1;
        ACT,,,QQ;
```

```
;       STATION 4 - CELL MANAGER

        CREATE,EXPON(XX(2)),,2;
J7      GOON,1;
        ACT,,0.45,T13;
        ACT,,0.1,T14;
        ACT,,0.2,T15;
        ACT,,0.25,T16;
T13     ASSIGN,ATRIB(5)=4,1;
        ACT,,,J8;
T14     ASSIGN,ATRIB(5)=3,1;
        ACT,,,J8;
T15     ASSIGN,ATRIB(5)=1,1;
        ACT,,,J8;
T16     ASSIGN,ATRIB(5)=2,1;
        ACT,,,J8;
J8      GOON,1;
        ASSIGN,ATRIB(1)=2,ATRIB(3)=20,ATRIB(4)=44;
        ASSIGN,ATRIB(6)=EXPON(XX(4)),1;
        ACT,,,QQ;

;       INTERNETWORK TRAFFIC

UVR     ASSIGN,ATRIB(3)=21,ATRIB(4)=45;
        ACT,,,QQ;
B2VR    ASSIGN,ATRIB(3)=22,ATRIB(4)=46;
        ACT,,,QQ;

;       GATED SERVICE BY TOKEN BUS U2

QQ      AWAIT(ATRIB(3)=17,22/100),ATRIB(3)/1;
        AWAIT(ATRIB(4)=41,46),ATRIB(3);
        ASSIGN,XX(16)=8*ATRIB(6)/XX(11)+184/XX(11)+0.006;
        ACT,XX(16);
        FREE,ATRIB(3);
        ACT,0.0835;
        ASSIGN,XX(16)=0;SET THE CURRENT SERVICE TIME = 0
        GOON,1;
        ACT,,ATRIB(5).EQ.4,TIS4;
        ACT,,ATRIB(5).EQ.3,VUT;
        ACT,,ATRIB(5).LT.3,VB2T;

;       COLLECT STATISTICS ON PACKETS DESTINED TO U2

TIS4    COLCT,INT(2),PKT DELAY4,,1;
        COLCT,BET,TIME BET. ARR4,,1;
```

```
        COLCT,ATRIB(6),PKT LEN4,,1;
        ACT,,,TIS;

;       SEND INTERNET TRAFFIC

VUT     QUEUE(55),,100;
        ACT,0.002+8*ATRIB(6)/XX(12),,VUR;Rec. buf. U1
VB2T    QUEUE(56),,100;
        ACT,0.002+8*ATRIB(6)/XX(12),,KB2R;Rec. buf. B1

;       BACKBONE MODULE - 2 BRIDGES

RB1R    ASSIGN,ATRIB(3)=23,ATRIB(4)=47;
        ACT,XX(9),,BRID;
KB2R    ASSIGN,ATRIB(3)=24,ATRIB(4)=48;
        ACT,XX(9),,BRID;

;       BACKBONE TOKEN BUS CYCLIC SERVICE

BRID    AWAIT(ATRIB(3)=23,24/100),ATRIB(3)/1;
        AWAIT(ATRIB(4)=47,48),ATRIB(3);
        ASSIGN,XX(17)=8*ATRIB(6)/XX(12)+184/XX(12)+0.006;
        ACT,XX(17);
        FREE,ATRIB(3);
        ACT,0.05;
        ASSIGN,XX(17)=0;SET THE CURRENT SERVICE TIME = 0
        GOON,1;
        ACT,,ATRIB(5).LE.2,B1RT;
        ACT,,ATRIB(5).GT.2,B2KT;
B1RT    QUEUE(57),,100;
        ACT,XX(9),,B1;
B1      GOON,1;
        ACT,0.002+8*ATRIB(6)/XX(12),ATRIB(5).EQ.1,B1MR;
        ACT,0.002+8*ATRIB(6)/XX(12),ATRIB(5).EQ.2,B1NR;
B2KT    QUEUE(58),,100;
        ACT,XX(9),,B2;
B2      GOON,1;
        ACT,0.002+8*ATRIB(6)/XX(12),ATRIB(5).EQ.3,B2UR;
        ACT,0.002+8*ATRIB(6)/XX(12),ATRIB(5).EQ.4,B2VR;

;       COLLECT STAT. AFTER WARMING UP

TIS     GOON,1;
        ACT,,TNOW.LE.50,WARM;
        ACT,,,STA;
WARM    TERM;
```

```
STA    COLCT,INT(2),SYS PKT DELAY,,1;
       COLCT,BET,TIME BET. ARRSYS,,1;
       COLCT,ATRIB(6),SYS PKT LEN,,1;
       TERM,500;

;      TOKEN SYNCHRONIZATION

;       RING 1

        CREATE,,,,1;
        ACT;
LOP1    ASSIGN,ATRIB(1)=1,XX(5)=TNOW;
LOP     OPEN,ATRIB(1);
        ACT,0.001;
        CLOSE,ATRIB(1);
        ACT,XX(13);
        COLCT,XX(13),SERV TIME1,,1;
        ASSIGN,ATRIB(1)=ATRIB(1)+1;
        ACT;
        GOON,1;
        ACT,0.01,ATRIB(1).LE.5,LOP;
        ACT,0.01;
        ASSIGN,ATRIB(2)=TNOW-XX(5);
        COLCT,ATRIB(2),SCAN TIME1,,1;
        ACT,,,LOP1;

;       RING 2

        CREATE,,,,1;
        ACT;
LP1     ASSIGN,ATRIB(1)=6,XX(6)=TNOW;
LP      OPEN,ATRIB(1);
        ACT,0.001;
        CLOSE,ATRIB(1);
        ACT,XX(14);
        COLCT,XX(14),SERV TIME2,,1;
        ASSIGN,ATRIB(1)=ATRIB(1)+1;
        ACT;
        GOON,1;
        ACT,0.01,ATRIB(1).LE.10,LP;
        ACT,0.01;
        ASSIGN,ATRIB(2)=TNOW-XX(6);
        COLCT,ATRIB(2),SCAN TIME2,,1;
        ACT,,,LP1;
```

```
;       BUS 1

        CREATE,,,,1;
        ACT;
L1      ASSIGN,ATRIB(1)=11,XX(7)=TNOW;
L       OPEN,ATRIB(1);
        ACT,0.001;
        CLOSE,ATRIB(1);
        COLCT,XX(15),SERV TIME3,,1;
        GOON,1;
        ACT,,XX(15).EQ.0,SUC1;
        ACT,XX(15)+0.0835;
SUC1    ASSIGN,ATRIB(1)=ATRIB(1)+1;
        ACT;
        GOON,1;
        ACT,,ATRIB(1).LE.16,L;
        ACT,0.125;
        ASSIGN,ATRIB(2)=TNOW-XX(7);
        COLCT,ATRIB(2),SCAN TIME3,,1;
        ACT,,,L1;


;       BUS 2

        CREATE,,,,1;
        ACT;
LL1     ASSIGN,ATRIB(1)=17,XX(8)=TNOW;
LL      OPEN,ATRIB(1);
        ACT,0.001;
        CLOSE,ATRIB(1);
        COLCT,XX(16),SERV TIME4,,1;
        GOON,1;
        ACT,,XX(16).EQ.0,SUC2;
        ACT,XX(16)+0.0835;
SUC2    ASSIGN,ATRIB(1)=ATRIB(1)+1;
        ACT;
        GOON,1;
        ACT,,ATRIB(1).LE.22,LL;
        ACT,0.125;
        ASSIGN,ATRIB(2)=TNOW-XX(8);
        COLCT,ATRIB(2),SCANTIME4,,1;
        ACT,,,LL1;


;       BACKBONE


        CREATE,,,,1;
```

```
       ACT;
LLL1   ASSIGN,ATRIB(1)=23,XX(18)=TNOW;
LLL    OPEN,ATRIB(1);
       ACT,0.001;
       CLOSE,ATRIB(1);
       COLCT,XX(17),SERV TIMES,,1;
       GOON,1;
       ACT,,XX(17).EQ.0,SUC3;
       ACT,XX(17)+0.05;
SUC3   ASSIGN,ATRIB(1)=ATRIB(1)+1;
       ACT;
       GOON,1;
       ACT,,ATRIB(1).LE.24,LLL;
       ACT,0.125;
       ASSIGN,ATRIB(2)=TNOW-XX(18);
       COLCT,ATRIB(2),SCAN TIMES,,1;
       ACT,,,LLL1;
       END;

INIT,0,1E+4; LIMIT MAXIMUM TIME OF SIMULATION
MONTR,CLEAR,50;CLEAR ALL STAT. ARRAYS AFTER 50 ms.
SIMULATE;

;      CHANGE EXPERIMENTAL CONDITIONS


INTLC,XX(2)=10,XX(4)=250,XX(11)=5E3,XX(10)=4E3;
SEEDS,3324611/Y;
MONTR,CLEAR,50;
SIMULATE;

INTLC,XX(2)=10,XX(4)=250,XX(11)=10E3,XX(10)=2E3;
SEEDS,3324611/Y;
MONTR,CLEAR,50;
SIMULATE;

INTLC,XX(2)=10,XX(4)=250,XX(11)=10E3,XX(10)=4E3;
SEEDS,3324611/Y;
MONTR,CLEAR,50;
SIMULATE;

INTLC,XX(2)=10,XX(4)=500,XX(11)=5E3,XX(10)=2E3;
SEEDS,3324611/Y;
MONTR,CLEAR,50;
SIMULATE;
```

```
INTLC,XX(2)=10,XX(4)=500,XX(11)=5E3,XX(10)=4E3;
SEEDS,3324611/Y;
MONTR,CLEAR,50;
SIMULATE;

INTLC,XX(2)=10,XX(4)=500,XX(11)=10E3,XX(10)=2E3;
SEEDS,3324611/Y;
MONTR,CLEAR,50;
SIMULATE;

INTLC,XX(2)=10,XX(4)=500,XX(11)=10E3,XX(10)=4E3;
SEEDS,3324611/Y;
MONTR,CLEAR,50;
SIMULATE;

INTLC,XX(2)=5,XX(4)=250,XX(11)=5E3,XX(10)=2E3;
SEEDS,3324611/Y;
MONTR,CLEAR,50;
SIMULATE;

INTLC,XX(2)=5,XX(4)=250,XX(11)=5E3,XX(10)=4E3;
SEEDS,3324611/Y;
MONTR,CLEAR,50;
SIMULATE;

INTLC,XX(2)=5,XX(4)=250,XX(11)=10E3,XX(10)=2E3;
SEEDS,3324611/Y;
MONTR,CLEAR,50;
SIMULATE;

INTLC,XX(2)=5,XX(4)=250,XX(11)=10E3,XX(10)=4E3;
SEEDS,3324611/Y;
MONTR,CLEAR,50;
SIMULATE;

INTLC,XX(2)=5,XX(4)=500,XX(11)=5E3,XX(10)=2E3;
SEEDS,3324611/Y;
MONTR,CLEAR,50;
SIMULATE;

INTLC,XX(2)=5,XX(4)=500,XX(11)=5E3,XX(10)=4E3;
SEEDS,3324611/Y;
MONTR,CLEAR,50;
SIMULATE;

INTLC,XX(2)=5,XX(4)=500,XX(11)=10E3,XX(10)=2E3;
```

```
SEEDS,3324611/Y;
MONTR,CLEAR,50;
SIMULATE;

INTLC,XX(2)=5,XX(4)=500,XX(11)=10E3,XX(10)=4E3;
SEEDS,3324611/Y;
MONTR,CLEAR,50;
SIMULATE;

FIN;
```

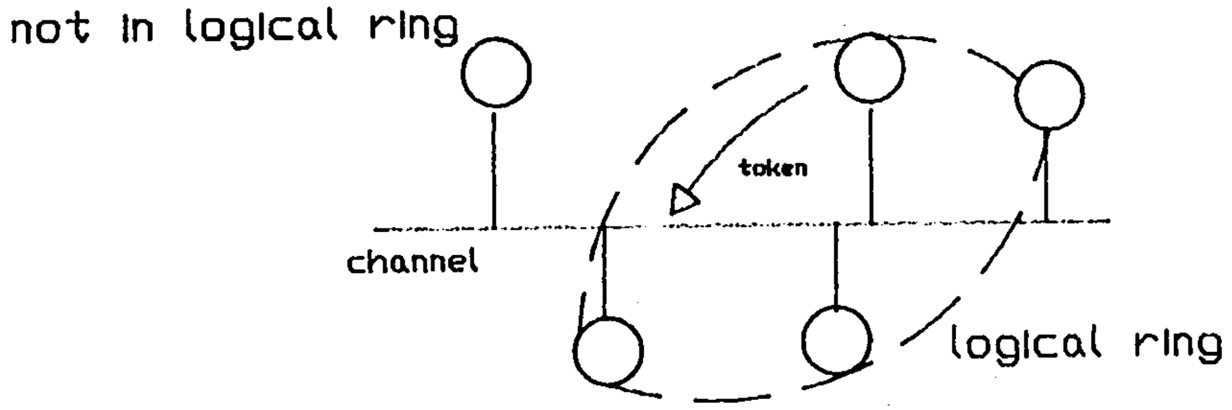


FIG 1. TOKEN BUS CONFIGURATION

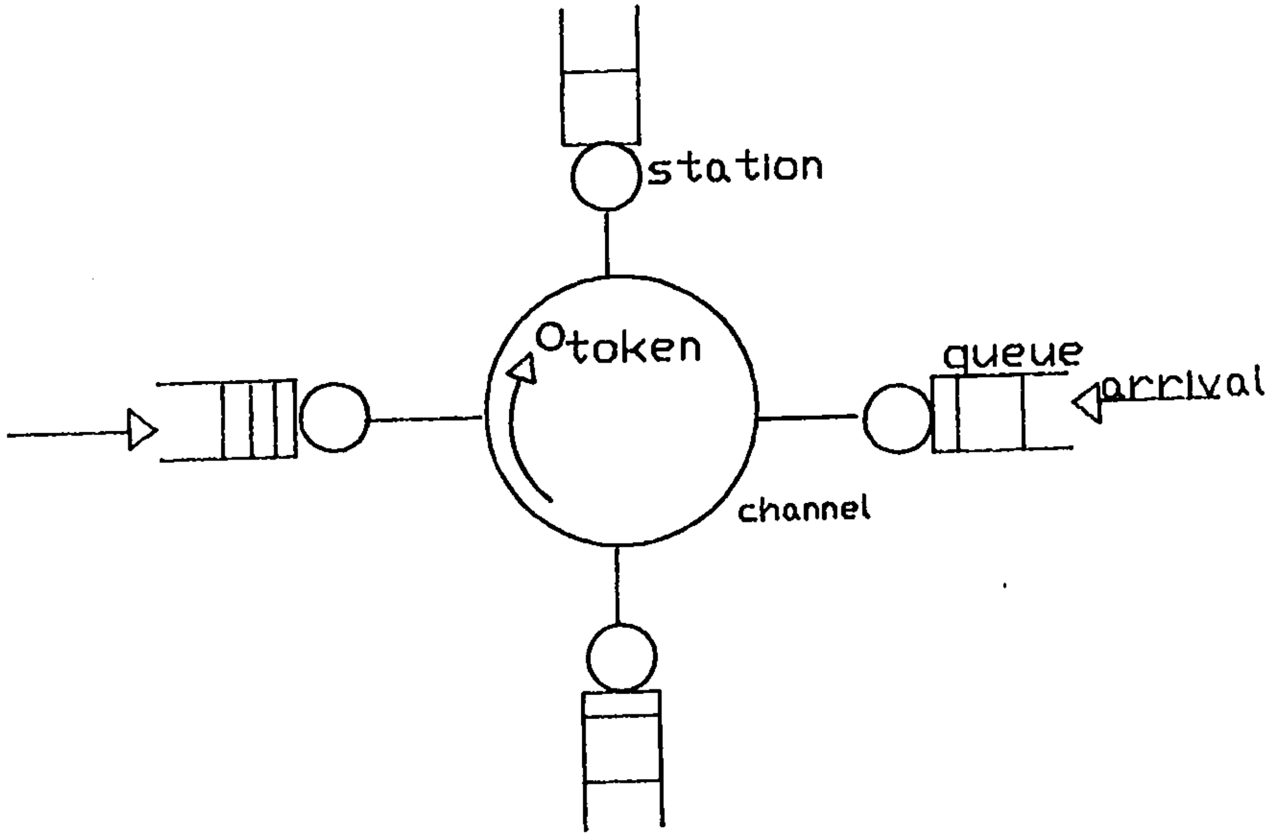


FIG 2. TOKEN RING CONFIGURATION

7	FTAM	DS	MMS
6	OSI PRESENTATION PROTOCOL (8823)		
5	OSI SESSION PROTOCOL (8327)		
4	CONNECTION ORIENTED TRANSPORT (8073)		
3	CONNECTIONLESS MODE (8473)		
2	LOGICAL LINK CONTROL (8802/2)		
1	TOKEN BUS (8802/4)		

MAP

FTAM	DS	VTP	MHS
OSI PRESENTATION PROTOCOL (8823)			
OSI SESSION PROTOCOL (8327)			
CONNECTION ORIENTED TRANSPORT(8073)			
CONNECTIONLESS MODE (8473)			
LOGICAL LINK CONTROL (8802/2)			
ETHERNET (8802/3)		TOKEN RING (8802/5)	

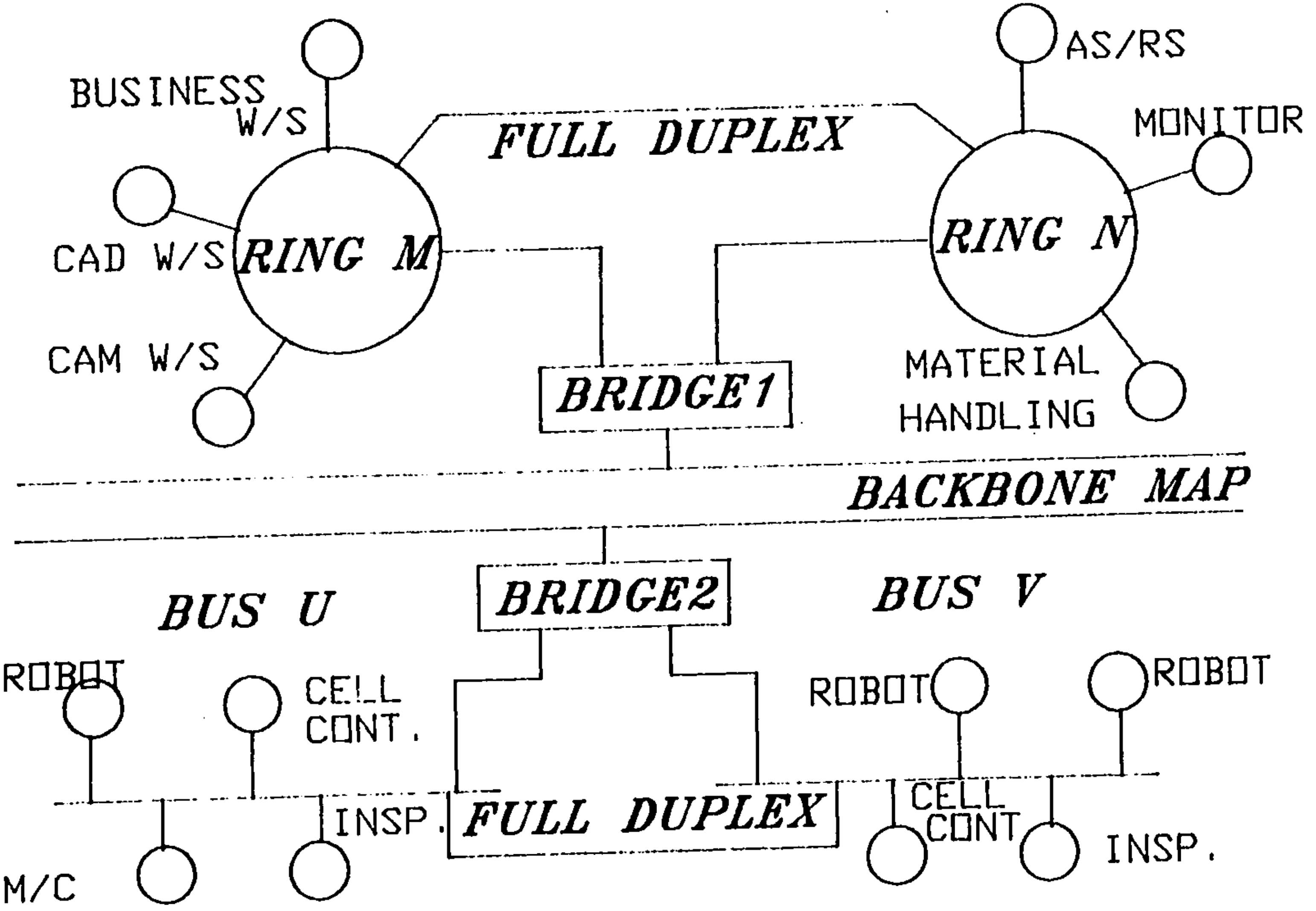
TOP

FTAM:	File Transfer Access Management
DS:	Directory Services
VTP:	Virtual Terminal Protocol
MHS:	Message Handling System
MMS:	Manufacturing Message Standard

FIG 3 MAP/TOP PROTOCOLS

FIG 4

COMMUNICATION NETWORK CONFIGURATION



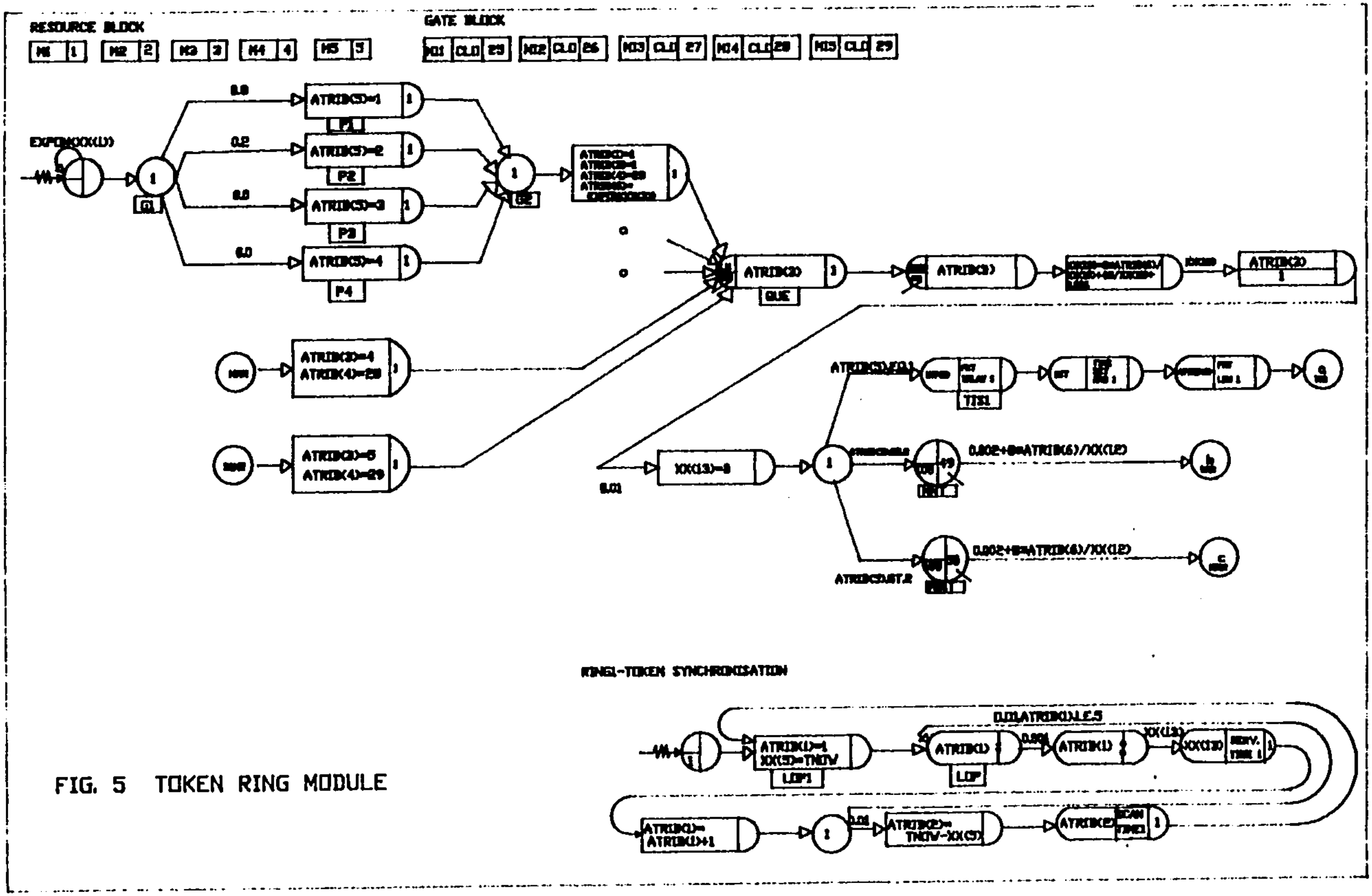
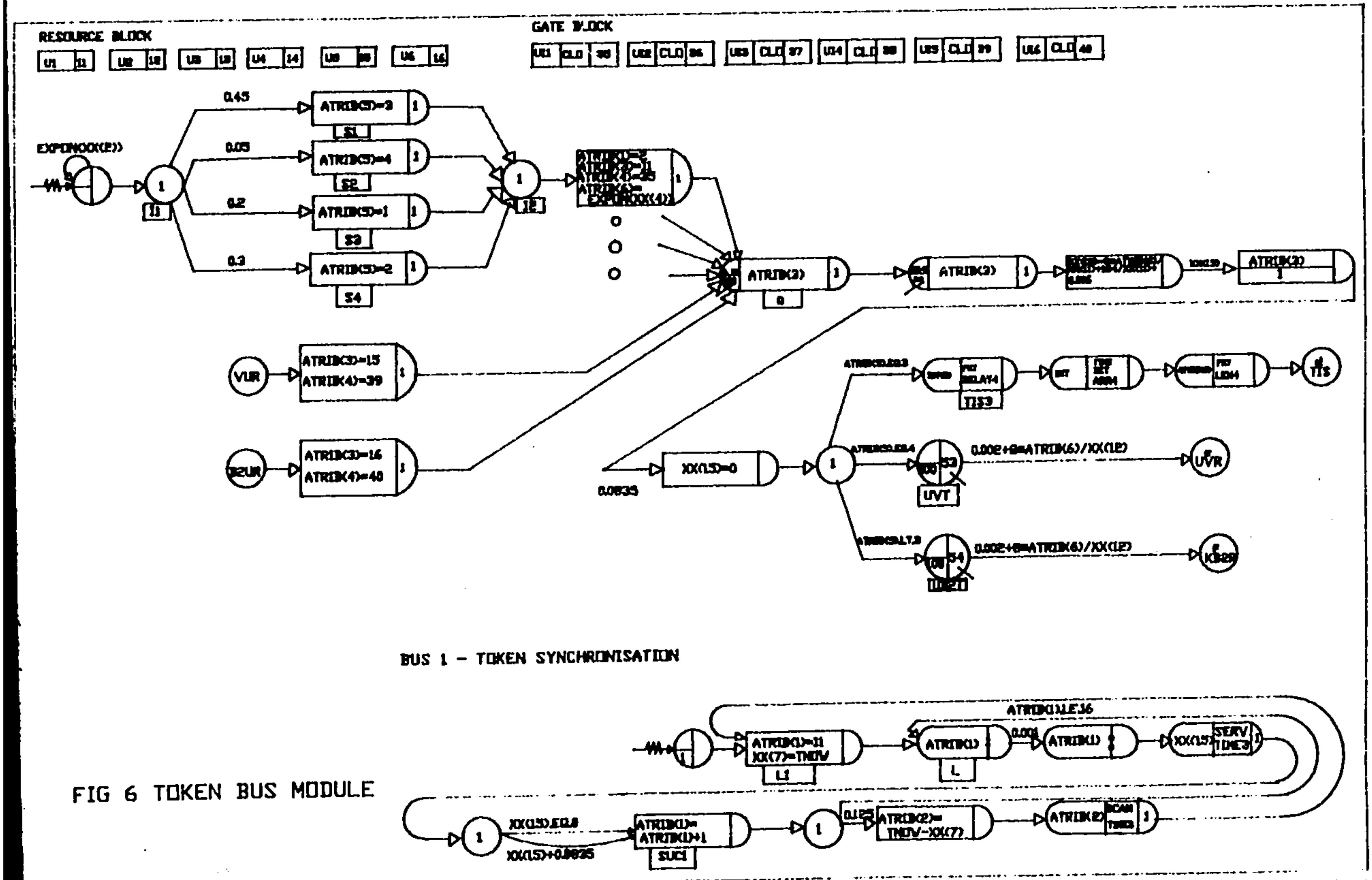


FIG. 5 TOKEN RING MODULE



BUS 1 - TOKEN SYNCHRONISATION

FIG 6 TOKEN BUS MODULE

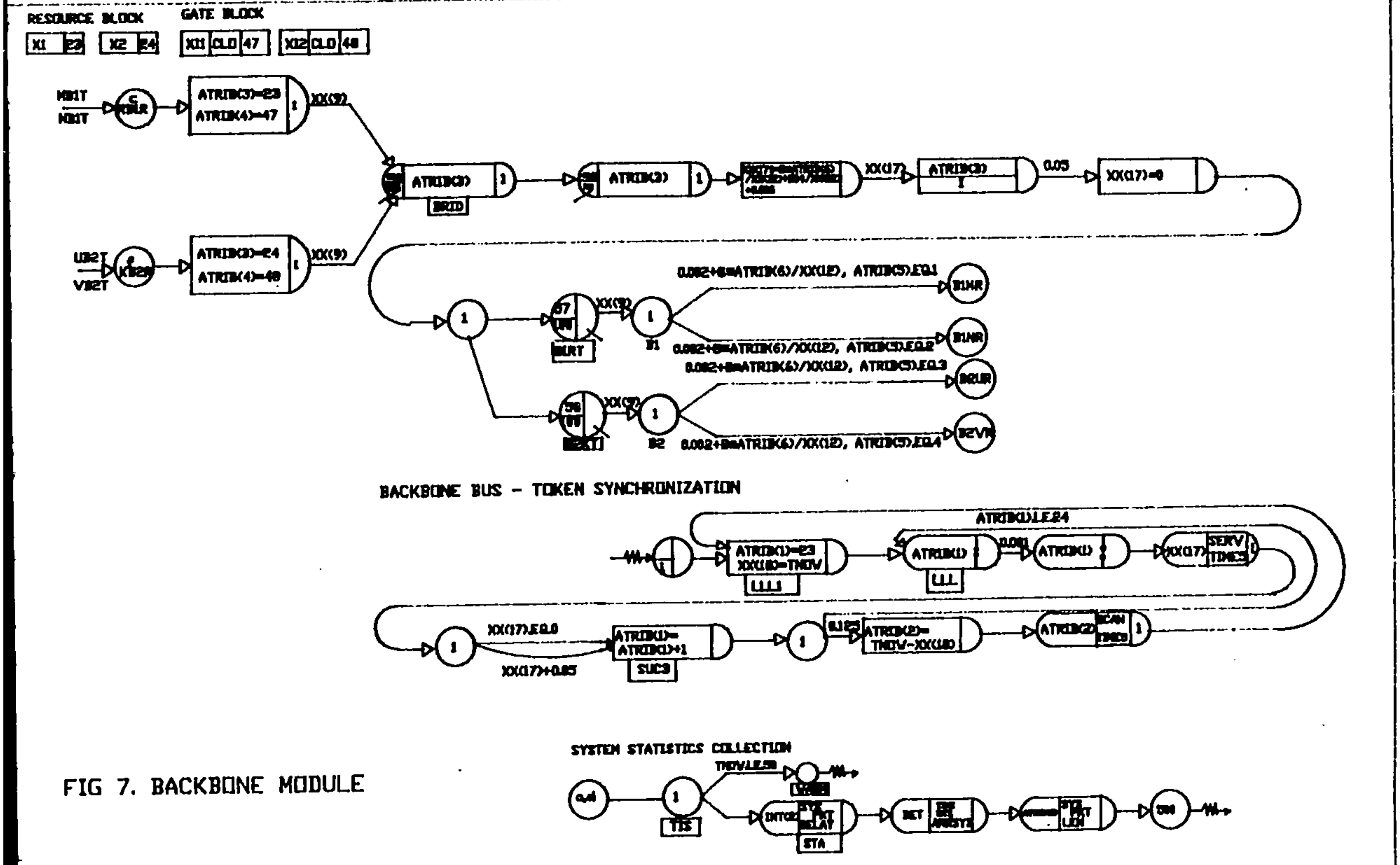


FIG 7. BACKBONE MODULE

FIGURE 8

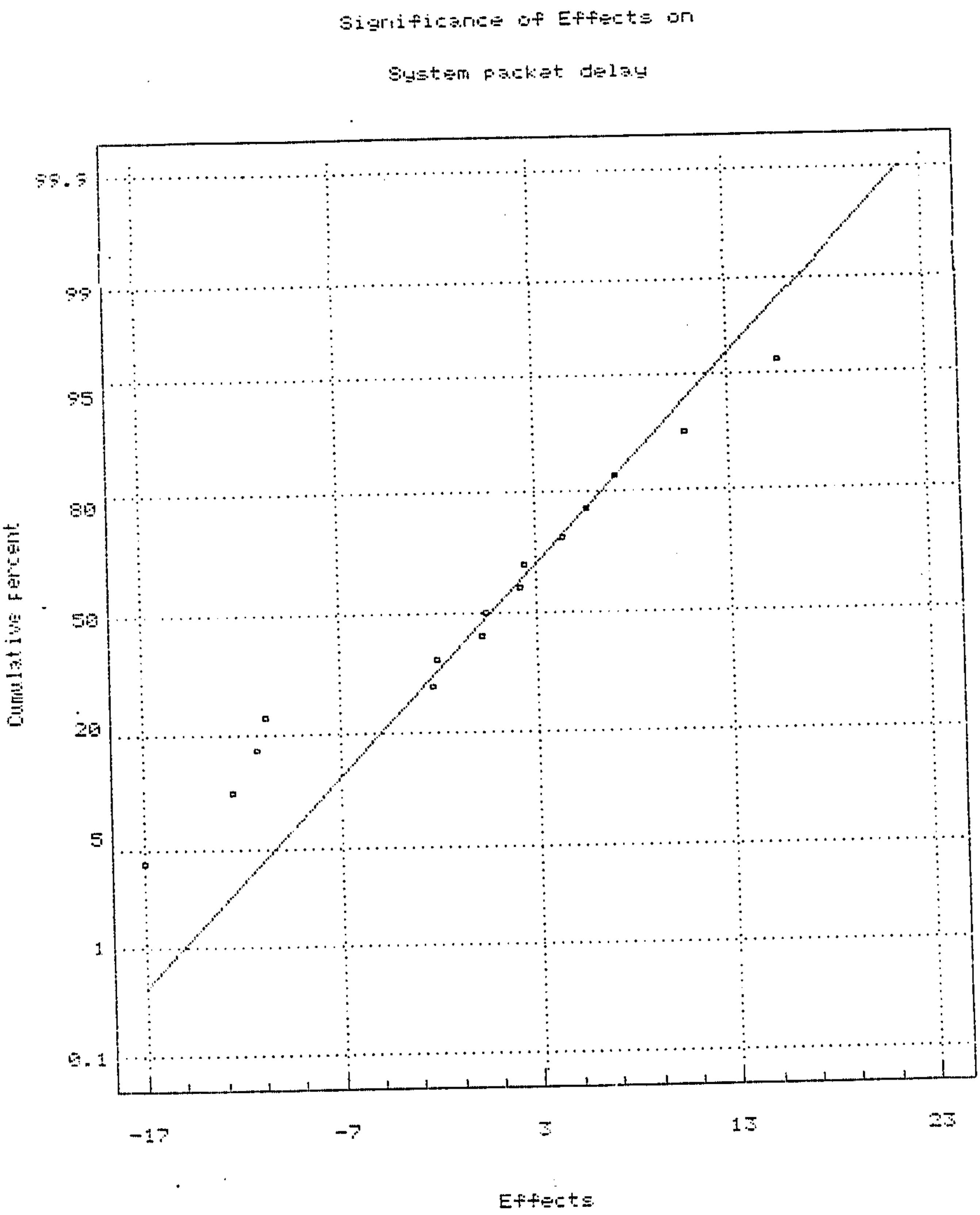

Significance of Effects on
System packet delay
99.9
99
95
80
50
20
5
1
0.1
Cumulative Percent
-17
-7
3
13
23
Effects

FIGURE 9

SIGNIFICANCE OF EFFECTS ON

SYSTEM THROUGHPUT

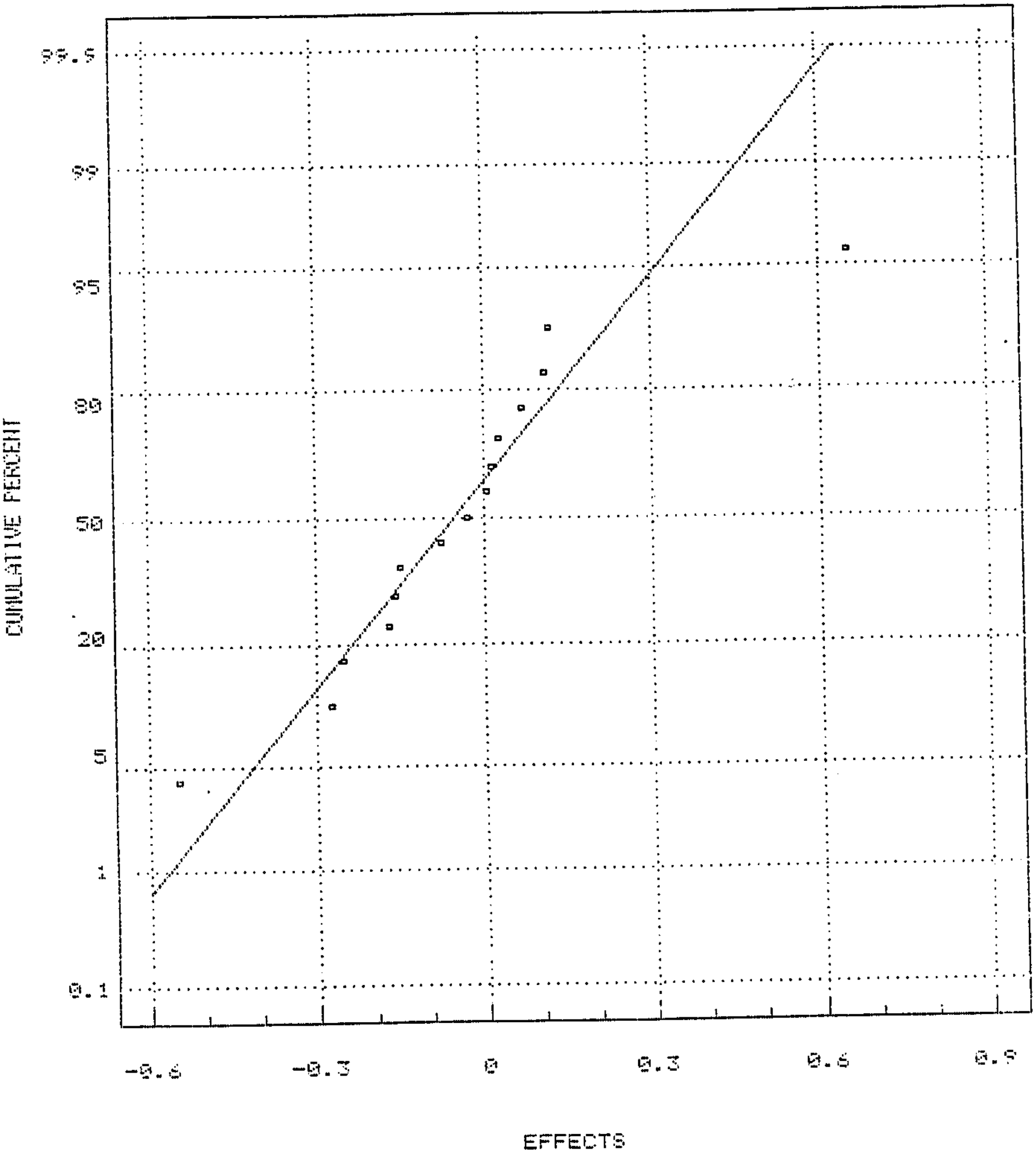


FIGURE 10

SIGNIFICANCE OF EFFECTS ON SCAN TIME OF

ASSEMBLY CELL NETWORK

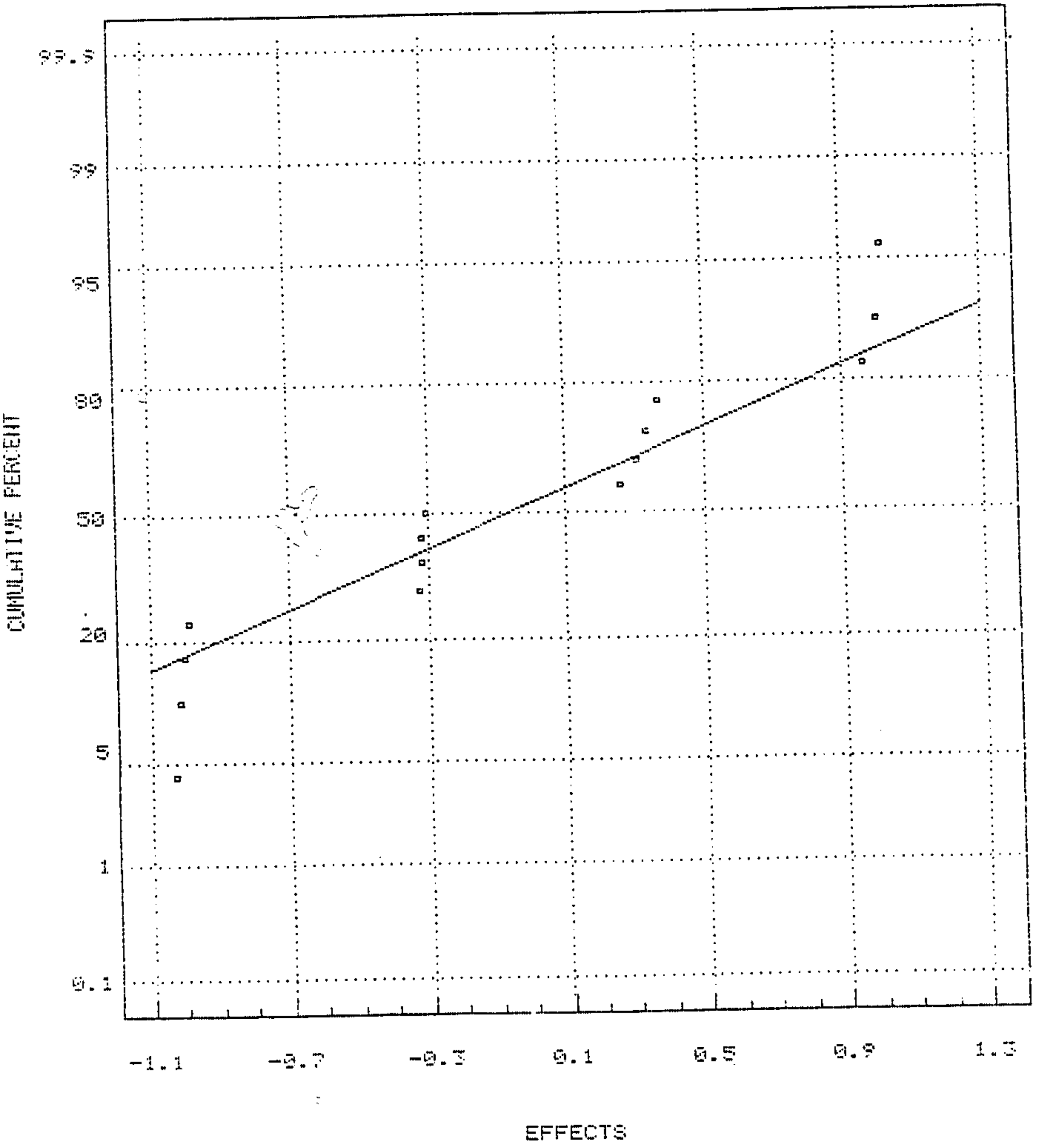


FIGURE 11

SIGNIFICANCE OF FACTOR EFFECTS ON

UTILISATION OF ASSEMBLY CELL NETWORK

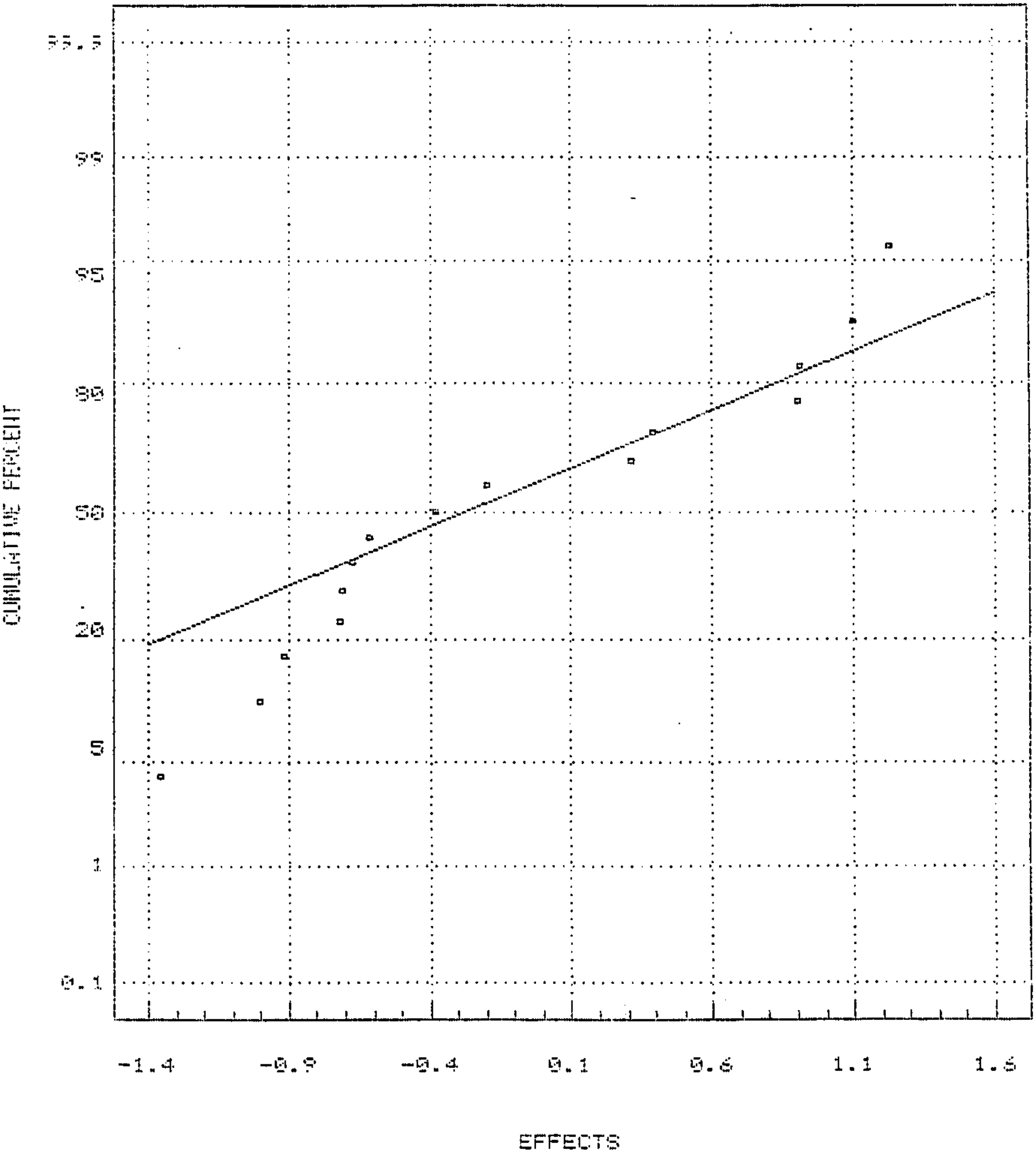


FIGURE 12

SIGNIFICANCE OF FACTOR EFFECTS ON

THROUGHPUT OF ASSEMBLY CELL NETWORK

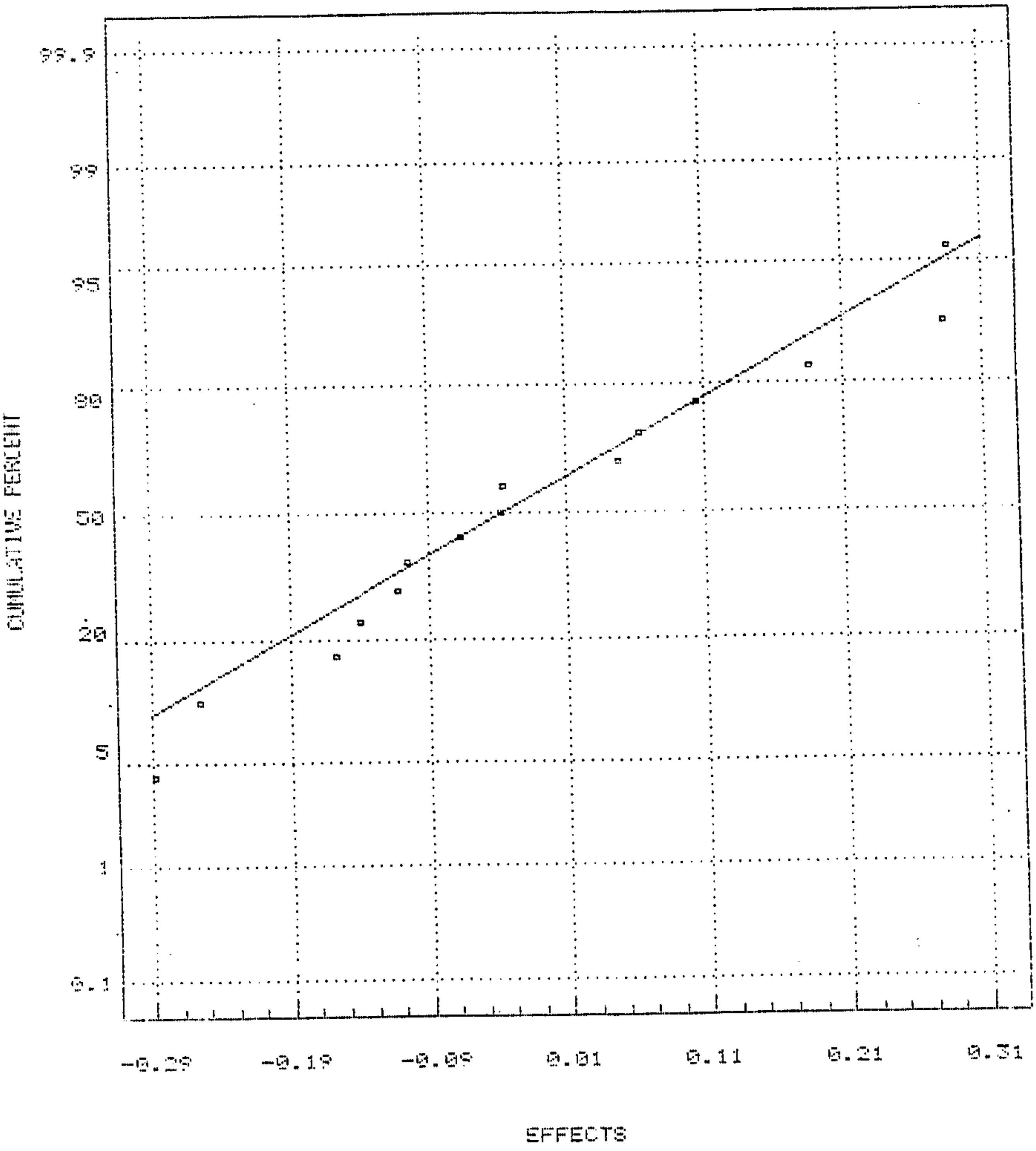
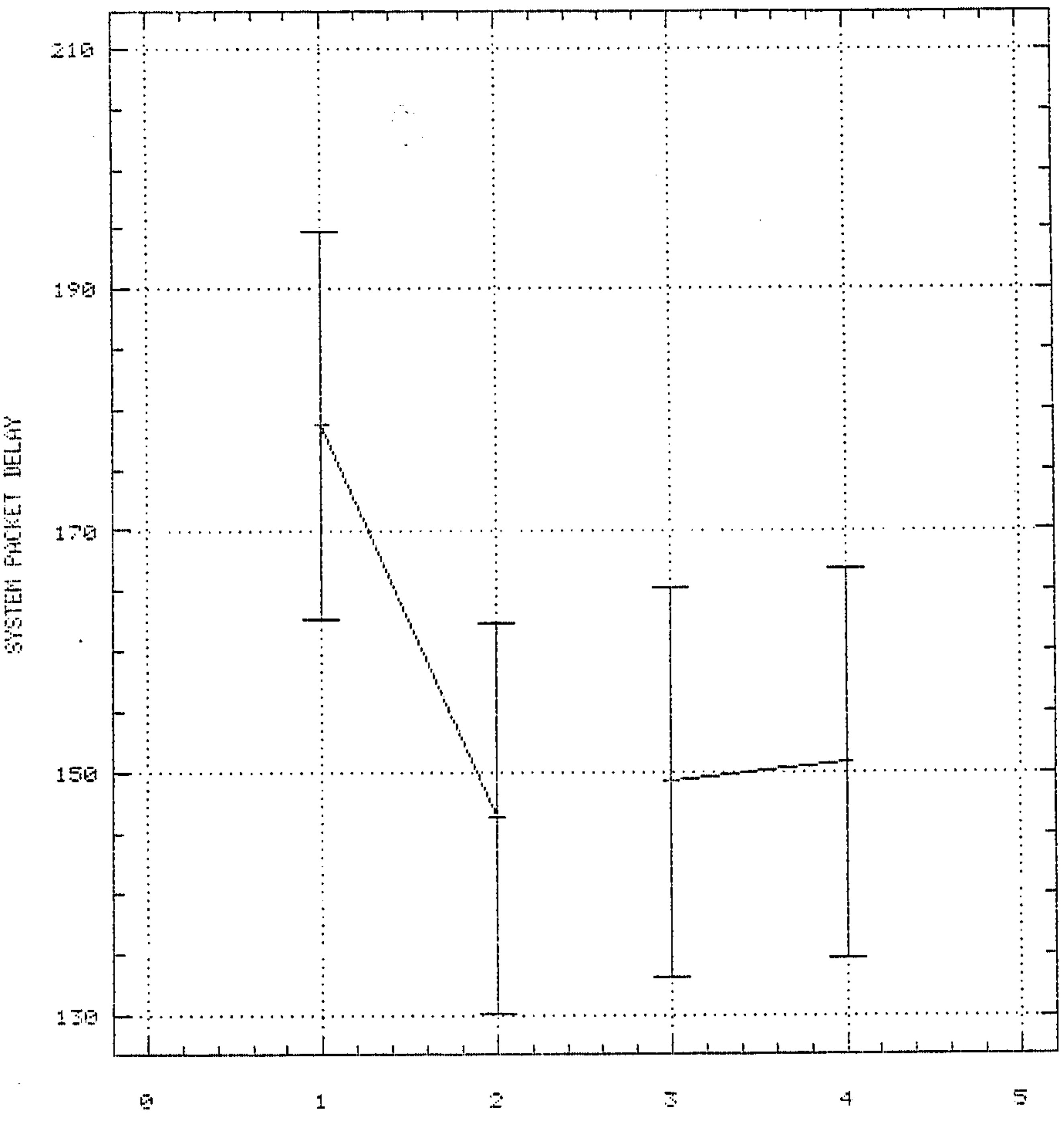


FIGURE 13

95 PERCENT CONFIDENCE INTERVALS FOR

SIGNIFICANT FACTOR MEANS



LEVEL OF B BY D

SYSTEM PACKET DELAY IN MILLISECS

FIGURE 14

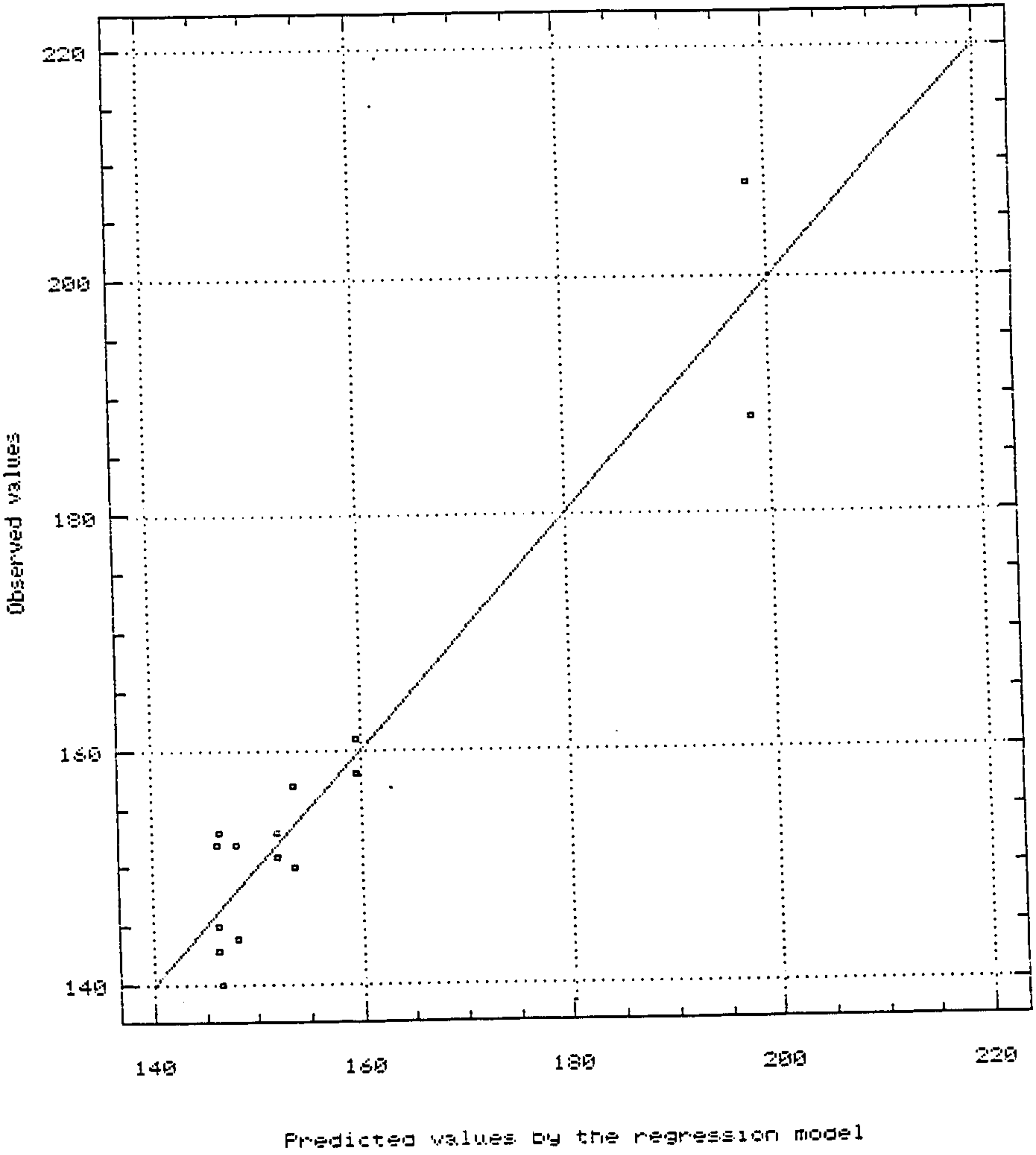


TABLE 3

Estimates of factor effects on system packet delay

```
--------------------------
     aver= 156.25
     A    =  -2.25
     B    = -12.5
     AB   =   2.25
     C    =   5.75
     AC   =  -2
     BC   = -11.25
     ABC  =   4.5
     D    =  15.5
     AD   =   0.25
     BD   = -17
     ABD  =   7.25
     CD   =  10.75
     ACD  =   0.5
     BCD  = -10.75
     ABCD=    2.5
--------------------------
```

TABLE 4.

Estimates of factor effects on throughput

```
-------------------------
aver=  5.633
A    = -0.2535
B    = -0.15075
AB   =  0.11725
C    = -0.0275
AC   =  0.026
BC   = -0.27675
ABC  = -0.15875
D    = -0.075
AD   = -0.1735
BD   =  0.06925
ABD  =  6.25E-3
CD   =  0.6515
ACD  =  0.016
BCD  = -0.54675
ABCD=  0.11025
-------------------------
```

TABLE 5

Estimates of factor effects on scan time of assembly cell network

```
---------------------------
      aver=  0.88575
      A    = -0.32075
      B    = -1.0145
      AB   =  0.36875
      C    =  0.95875
      AC   = -0.324
      BC   = -1.00225
      ABC  =  0.2585
      D    =  1.001
      AD   = -0.32025
      BD   = -0.9885
      ABD  =  0.33375
      CD   =  1.01675
      ACD  = -0.306
      BCD  = -1.03375
      ABCD=  0.301
---------------------------
```

TABLE 6

Estimates of factor effects on utilisation of assembly cell network

```
aver=  9.64313
A    = -0.61625
B    = -1.00625
AB   =  1.22625
C    =  0.38875
AC   = -0.67375
BC   = -0.91375
ABC  = -0.20125
D    =  0.89625
AD   = -0.70625
BD   = -0.71625
ABD  =  0.90625
CD   =  1.09875
ACD  = -0.38375
BCD  = -1.35375
ABCD=  0.30875
```

TABLE 7

Estimates of factor effects on throughput of assembly cell network

```
---------------------------
      aver=  1.815
      A    = -0.035
      B    = -0.255
      AB   =  0.285
      C    =  0.0625
      AC   = -0.1125
      BC   = -0.1575
      ABC  = -0.0675
      D    =  0.105
      AD   = -0.105
      BD   = -0.14
      ABD  =  0.185
      CD   =  0.2825
      ACD  = -0.0375
      BCD  = -0.2875
      ABCD=  0.0475
---------------------------
```

TABLE 8

Analysis of Variance for System packet delay

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	1738.5000	4	434.62500	2.788	.1454
A	20.2500	1	20.25000	.130	.7369
B	625.0000	1	625.00000	4.009	.1016
C	132.2500	1	132.25000	.848	.4087
D	961.0000	1	961.00000	6.164	.0557
2-FACTOR INTERACTIONS	2161.0000	6	360.1667	2.310	.1882
A B	20.2500	1	20.2500	.130	.7369
A C	16.0000	1	16.0000	.103	.7649
B C	506.2500	1	506.2500	3.247	.1314
A D	.2500	1	.2500	.002	.9700
B D	1156.0000	1	1156.0000	7.415	.0416
C D	462.2500	1	462.2500	2.965	.1457
RESIDUAL	779.50000	5	155.90000		
TOTAL (CORR.)	4679.0000	15			

TABLE 9

Table of means for System packet delay

Level	Count	Average	Stnd. Error (internal)	Stnd. Error (pooled s)	95 Percent Confidence for mean	
A						
2	8	157.37500	7.622658	4.4144649	146.02359	168.72641
4	8	155.12500	5.008698	4.4144649	143.77359	166.47641
B						
5	8	162.50000	8.287254	4.4144649	151.14859	173.85141
10	8	150.00000	1.927248	4.4144649	138.64859	161.35141
C						
250	8	153.37500	1.802156	4.4144649	142.02359	164.72641
500	8	159.12500	8.828601	4.4144649	147.77359	170.47641
D						
5	8	164.00000	7.955232	4.4144649	152.64859	175.35141
10	8	148.50000	1.762709	4.4144649	137.14859	159.85141
A by B						
2 5	4	164.75000	14.901762	6.2429961	148.69669	180.80331
Total	16	156.25000	3.121498	3.1214980	148.22334	164.27666

TABLE 9 (Continued)
Table of means for System packet delay

Level	Count	Average	Stnd. Error (internal)	Stnd. Error (pooled s)	95 Percent Confidence for mean	
2 10	4	150.00000	3.582364	6.2429961	133.94669	166.05331
4 5	4	160.25000	9.750000	6.2429961	144.19669	176.30331
4 10	4	150.00000	2.121320	6.2429961	133.94669	166.05331
A by C						
2 250	4	153.50000	3.500000	6.2429961	137.44669	169.55331
2 500	4	161.25000	15.776433	6.2429961	145.19669	177.30331
4 250	4	153.25000	1.701715	6.2429961	137.19669	169.30331
4 500	4	157.00000	10.575128	6.2429961	140.94669	173.05331
B by C						
5 250	4	154.00000	3.535534	6.2429961	137.94669	170.05331
5 500	4	171.00000	16.119347	6.2429961	154.94669	187.05331
10 250	4	152.75000	1.547848	6.2429961	136.69669	168.80331
10 500	4	147.25000	3.145764	6.2429961	131.19669	163.30331
A by D						
Total	16	156.25000	3.121498	3.1214980	148.22334	164.27666

TABLE 9 (Continued)
Table of means for System packet delay

Level	Count	Average	Stnd. Error (internal)	Stnd. Error (pooled s)	95 Percent Confidence for mean	
2 5	4	165.00000	14.961061	6.2429961	148.94669	181.05331
2 10	4	149.75000	2.926175	6.2429961	133.69669	165.80331
4 5	4	163.00000	8.416254	6.2429961	146.94669	179.05331
4 10	4	147.25000	2.212653	6.2429961	131.19669	163.30331
B by D						
5 5	4	178.75000	11.855906	6.2429961	162.69669	194.80331
5 10	4	146.25000	1.973787	6.2429961	130.19669	162.30331
10 5	4	149.25000	3.119161	6.2429961	133.19669	165.30331
10 10	4	150.75000	2.688711	6.2429961	134.69669	166.80331
C by D						
250 5	4	155.75000	2.286737	6.2429961	139.69669	171.80331
250 10	4	151.00000	2.483277	6.2429961	134.94669	167.05331
500 5	4	172.25000	15.643822	6.2429961	156.19669	188.30331
500 10	4	146.00000	2.041241	6.2429961	129.94669	162.05331
Total	16	156.25000	3.121498	3.1214980	148.22334	164.27666

TABLE 10

Analysis of Variance for System throughput

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	.3734762	4	.0933691	.347	.8366
A	.2570490	1	.2570490	.955	.3834
B	.0909023	1	.0909023	.338	.5923
C	.0030250	1	.0030250	.011	.9208
D	.0225000	1	.0225000	.084	.7871
2-FACTOR INTERACTIONS	2.2014567	6	.3669095	1.363	.3758
A B	.0549903	1	.0549903	.204	.6749
A C	.0027040	1	.0027040	.010	.9251
B C	.3063623	1	.3063623	1.138	.3349
A D	.1204090	1	.1204090	.447	.5401
B D	.0191823	1	.0191823	.071	.8029
C D	1.6978090	1	1.6978090	6.305	.0538
RESIDUAL	1.3463490	5	.2692698		
TOTAL (CORR.)	3.9212820	15			

TABLE 11

Table of means for System throughput

Level	Count	Average	Stnd. Error (internal)	Stnd. Error (pooled s)	95 Percent Confidence for mean	
A						
2	8	5.7597500	.1830096	.1834631	5.2879907	6.2315093
4	8	5.5062500	.1787182	.1834631	5.0344907	5.9780093
B						
5	8	5.7083750	.2486763	.1834631	5.2366157	6.1801343
10	8	5.5576250	.0809920	.1834631	5.0858657	6.0293843
C						
250	8	5.6467500	.2003708	.1834631	5.1749907	6.1185093
500	8	5.6192500	.1726859	.1834631	5.1474907	6.0910093
D						
5	8	5.5955000	.2134636	.1834631	5.1237407	6.0672593
10	8	5.6705000	.1550948	.1834631	5.1987407	6.1422593
A by B						
2 5	4	5.8937500	.3737174	.2594561	5.2265816	6.5609184
Total	16	5.6330000	.1297280	.1297280	5.2994158	5.9665842

TABLE 11 (Continued)
Table of means for System throughput

```
--------------------------------------------------------------------------------------
                                   Stnd. Error  Stnd. Error    95 Percent Confidence
Level      Count        Average    (internal)   (pooled s)            for mean
--------------------------------------------------------------------------------------
 2    10       4      5.6257500     .0682866     .2594561     4.9585816     6.2929184
 4     5       4      5.5230000     .3549822     .2594561     4.8558316     6.1901684
 4    10       4      5.4895000     .1511784     .2594561     4.8223316     6.1566684
A by C
 2   250       4      5.7865000     .2628797     .2594561     5.1193316     6.4536684
 2   500       4      5.7330000     .2944752     .2594561     5.0658316     6.4001684
 4   250       4      5.5070000     .3243974     .2594561     4.8398316     6.1741684
 4   500       4      5.5055000     .2093329     .2594561     4.8383316     6.1726684
B by C
  5  250       4      5.5837500     .4201385     .2594561     4.9165816     6.2509184
  5  500       4      5.8330000     .3189289     .2594561     5.1658316     6.5001684
 10  250       4      5.7097500     .0905376     .2594561     5.0425816     6.3769184
 10  500       4      5.4055000     .0835878     .2594561     4.7383316     6.0726684
A by D
--------------------------------------------------------------------------------------
Total         16      5.6330000     .1297280     .1297280     5.2994158     5.9665842
```

TABLE II (Continued)
Table of means for System throughput

Level		Count	Average	Stnd. Error (internal)	Stnd. Error (pooled s)	95 Percent Confidence for mean	
2	5	4	5.8090000	.2859741	.2594561	5.1418316	6.4761684
2	10	4	5.7105000	.2700005	.2594561	5.0433316	6.3776684
4	5	4	5.3820000	.3169784	.2594561	4.7148316	6.0491684
4	10	4	5.6305000	.1956704	.2594561	4.9633316	6.2976684
B by D							
5	5	4	5.6362500	.4478185	.2594561	4.9690816	6.3034184
5	10	4	5.7805000	.2908211	.2594561	5.1133316	6.4476684
10	5	4	5.5547500	.1048629	.2594561	4.8875816	6.2219184
10	10	4	5.5605000	.1400366	.2594561	4.8933316	6.2276684
C by D							
250	5	4	5.2835000	.2582165	.2594561	4.6163316	5.9506684
250	10	4	6.0100000	.1808775	.2594561	5.3428316	6.6771684
500	5	4	5.9075000	.2847331	.2594561	5.2403316	6.5746684
500	10	4	5.3310000	.0519326	.2594561	4.6638316	5.9981684
Total		16	5.6330000	.1297280	.1297280	5.2994158	5.9665842

TABLE 12

Analysis of Variance for Scan time of assembly net.

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	12.213174	4	3.0532934	2.667	.1555
A	.411522	1	.4115223	.359	.5810
B	4.116841	1	4.1168410	3.596	.1164
C	3.676806	1	3.6768062	3.212	.1331
D	4.008004	1	4.0080040	3.501	.1203
2-FACTOR INTERACTIONS	13.435722	6	2.2392870	1.956	.2393
A B	.543906	1	.5439063	.475	.5283
A C	.419904	1	.4199040	.367	.5774
B C	4.018020	1	4.0180202	3.510	.1199
A D	.410240	1	.4102402	.358	.5816
B D	3.908529	1	3.9085290	3.414	.1239
C D	4.135122	1	4.1351223	3.612	.1158
RESIDUAL	5.7243495	5	1.1448699		
TOTAL (CORR.)	31.373245	15			

TABLE 13

Table of means for Scan time of assembly net.

Level	Count	Average	Stnd. Error (internal)	Stnd. Error (pooled s)	95 Percent Confidence for mean	
A						
2	8	1.0461250	.6593717	.3782972	.0733672	2.0188828
4	8	.7253750	.3436813	.3782972	-.2473828	1.6981328
B						
5	8	1.3930000	.6974203	.3782972	.4202422	2.3657578
10	8	.3785000	.0180663	.3782972	-.5942578	1.3512578
C						
250	8	.4063750	.0238200	.3782972	-.5663828	1.3791328
500	8	1.3651250	.7028598	.3782972	.3923672	2.3378828
D						
5	8	1.3862500	.6988315	.3782972	.4134922	2.3590078
10	8	.3852500	.0173079	.3782972	-.5875078	1.3580078
A by B						
2 5	4	1.7377500	1.3076630	.5349930	.3620627	3.1134373
Total	16	.8857500	.2674965	.2674965	.1979063	1.5735937

TABLE 15(Continued)

Table of means for Scan time of assembly cell net.

Level	Count	Average	Stnd. Error (internal)	Stnd. Error (pooled s)	95 Percent Confidence for mean	
2 10	4	.3545000	.0072399	.5349930	-1.0211873	1.7301873
4 5	4	1.0482500	.6932721	.5349930	-.3274373	2.4239373
4 10	4	.4025000	.0329659	.5349930	-.9731873	1.7781873
A by C						
2 250	4	.4047500	.0355490	.5349930	-.9709373	1.7804373
2 500	4	1.6875000	1.3241702	.5349930	.3118127	3.0631873
4 250	4	.4080000	.0371797	.5349930	-.9676873	1.7836873
4 500	4	1.0427500	.6947505	.5349930	-.3329373	2.4184373
B by C						
5 250	4	.4125000	.0380559	.5349930	-.9631873	1.7881873
5 500	4	2.3735000	1.2757254	.5349930	.9978127	3.7491873
10 250	4	.4002500	.0342719	.5349930	-.9754373	1.7759373
10 500	4	.3567500	.0057645	.5349930	-1.0189373	1.7324373
A by D						
Total	16	.8857500	.2674965	.2674965	.1979063	1.5735937

TABLE 13 (Continued)
Table of means for Scan time of assembly cell net

Level		Count	Average	Stnd. Error (internal)	Stnd. Error (pooled s)	95 Percent Confidence for mean	
2	5	4	1.7067500	1.3179840	.5349930	.3310627	3.0824373
2	10	4	.3855000	.0299958	.5349930	-.9901873	1.7611873
4	5	4	1.0657500	.6880966	.5349930	-.3099373	2.4414373
4	10	4	.3850000	.0223196	.5349930	-.9906873	1.7606873
B by D							
5	5	4	2.3877500	1.2685962	.5349930	1.0120627	3.7634373
5	10	4	.3982500	.0286804	.5349930	-.9774373	1.7739373
10	5	4	.3847500	.0321620	.5349930	-.9909373	1.7604373
10	10	4	.3722500	.0215111	.5349930	-1.0034373	1.7479373
C by D							
250	5	4	.3985000	.0424843	.5349930	-.9771873	1.7741873
250	10	4	.4142500	.0283119	.5349930	-.9614373	1.7899373
500	5	4	2.3740000	1.2754609	.5349930	.9983127	3.7496873
500	10	4	.3562500	.0059774	.5349930	-1.0194373	1.7319373
Total		16	.8857500	.2674965	.2674965	.1979063	1.5735937

TABLE 14

Analysis of Variance for Utilisation of assembly cell net

Source of variation		Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS		9.3867750	4	2.3466937	.999	.4862
A		1.5190563	1	1.5190563	.647	.4660
B		4.0501562	1	4.0501562	1.724	.2462
C		.6045062	1	.6045062	.257	.6387
D		3.2130562	1	3.2130562	1.367	.2950
2-FACTOR INTERACTIONS		20.046487	6	3.3410812	1.422	.3581
A	B	6.014756	1	6.0147563	2.560	.1705
A	C	1.815756	1	1.8157562	.773	.4285
B	C	3.339756	1	3.3397563	1.421	.2867
A	D	1.995156	1	1.9951563	.849	.4084
B	D	2.052056	1	2.0520562	.873	.4024
C	D	4.829006	1	4.8290062	2.055	.2111
RESIDUAL		11.748081	5	2.3496163		
TOTAL (CORR.)		41.181344	15			

TABLE 15

Table of means for Utilisation of assembly cell network

Level	Count	Average	Stnd. Error (internal)	Stnd. Error (pooled s)	95 Percent Confidence for mean	
A						
2	8	9.951250	.7742011	.5419428	8.5576917	11.344808
4	8	9.335000	.3299513	.5419428	7.9414417	10.728558
B						
5	8	10.146250	.7794044	.5419428	8.7526917	11.539808
10	8	9.140000	.2357662	.5419428	7.7464417	10.533558
C						
250	8	9.448750	.3250299	.5419428	8.0551917	10.842308
500	8	9.837500	.7867286	.5419428	8.4439417	11.231058
D						
5	8	10.091250	.7961435	.5419428	8.6976917	11.484808
10	8	9.195000	.2101445	.5419428	7.8014417	10.588558
A by B						
2 5	4	11.067500	1.3976848	.7664229	9.0967110	13.038289
Total	16	9.643125	.3832115	.3832115	8.6577305	10.628520

TABLE 15 (Continued)

Table of means for Utilisation of assembly cell network

Level	Count	Average	Stnd. Error (internal)	Stnd. Error (pooled s)	95 Percent Confidence for mean	
2 10	4	8.835000	.1137614	.7664229	6.8642110	10.805789
4 5	4	9.225000	.5617310	.7664229	7.2542110	11.195789
4 10	4	9.445000	.4294667	.7664229	7.4742110	11.415789
A by C						
2 250	4	9.420000	.4403029	.7664229	7.4492110	11.390789
2 500	4	10.482500	1.5540666	.7664229	8.5117110	12.453289
4 250	4	9.477500	.5464335	.7664229	7.5067110	11.448289
4 500	4	9.192500	.4426318	.7664229	7.2217110	11.163289
B by C						
5 250	4	9.495000	.5345481	.7664229	7.5242110	11.465789
5 500	4	10.797500	1.5054477	.7664229	8.8267110	12.768289
10 250	4	9.402500	.4536955	.7664229	7.4317110	11.373289
10 500	4	8.877500	.0873093	.7664229	6.9067110	10.848289
A by D						
Total	16	9.643125	.3832115	.3832115	8.6577305	10.628520

TABLE 15(Continued)
Table of means for Utilisation of assembly cell network

Level	Count	Average	Stnd. Error (internal)	Stnd. Error (pooled s)	95 Percent Confidence for mean	
2 5	4	10.752500	1.4994075	.7664229	8.7817110	12.723289
2 10	4	9.150000	.3477307	.7664229	7.1792110	11.120789
4 5	4	9.430000	.6466967	.7664229	7.4592110	11.400789
4 10	4	9.240000	.2895111	.7664229	7.2692110	11.210789
B by D						
5 5	4	10.952500	1.5109124	.7664229	8.9817110	12.923289
5 10	4	9.340000	.3444561	.7664229	7.3692110	11.310789
10 5	4	9.230000	.4249510	.7664229	7.2592110	11.200789
10 10	4	9.050000	.2709551	.7664229	7.0792110	11.020789
C by D						
250 5	4	9.347500	.6101827	.7664229	7.3767110	11.318289
250 10	4	9.550000	.3374167	.7664229	7.5792110	11.520789
500 5	4	10.835000	1.4889062	.7664229	8.8642110	12.805789
500 10	4	8.840000	.0906458	.7664229	6.8692110	10.810789
Total	16	9.643125	.3832115	.3832115	8.6577305	10.628520

TABLE 16

Regression model fitting results for System packet delay

```
---------------------------------------------------------------------------------------------
Independent variable                       coefficient  std. error       t-value   sig.level
---------------------------------------------------------------------------------------------
CONSTANT                                        146.25    3.309288       44.1932      0.0000
B*D                                             -14.75    8.755554       -1.6846      0.1263
B*C                                               -5.5    6.618577       -0.8310      0.4275
B                                                 7.25    5.731855        1.2649      0.2377
B*C*D                                            -38.5   11.463711       -3.3584      0.0084
D                                                13.25    5.731855        2.3116      0.0461
C*D                                               38.5    6.618577        5.8170      0.0003
---------------------------------------------------------------------------------------------
R-SQ. (ADJ.) = 0.8596   SE=          6.618577  MAE=          4.031250  Durbwat=   2.370
Previously:     0.0000               0.000000                0.000000               0.000
16 observations fitted, forecast(s) computed for 0 missing val. of dep. var.


                       Analysis of Variance for the Full Regression
---------------------------------------------------------------------------------------------
Source                     Sum of Squares      DF     Mean Square         F-Ratio    P-value
---------------------------------------------------------------------------------------------
Model                             4284.75       6         714.125         16.3022      .0002
Error                             394.250       9         43.8056
---------------------------------------------------------------------------------------------
Total (Corr.)                     4679.00      15

R-squared = 0.915741                                   Stnd. error of est. = 6.61858
R-squared (Adj. for d.f.) = 0.859568               Durbin-Watson statistic = 2.37016
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VITA AUCTORIS

1965	Born in Tirumangalam, India on the 11th of May.
1980	Completed secondary school education from Government higher secondary school, Vridhachalam, India, securing first division.
1982	Completed higher secondary school education from Kalyanasundaram higher secondary school, Thanjavur, India, securing first division.
1986	Graduated from the College of Engineering, Anna University, Madras, India with a Bachelor of Engineering Degree in Mechanical Engineering, securing first division with distinction.
1988	Graduated from the Indian Institute of Technology, Madras, India with a Master of Technology Degree in Mechanical Engineering, securing first division with distinction.
1989	Currently a candidate for the M. A. Sc. Degree in Industrial Engineering at the University of Windsor, Windsor, Ontario, Canada.