

ROUTING IN PACKET SWITCHED COMPUTER COMMUNICATION NETWORKS

BY

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ABSTRACT

This thesis concerns the optimization of the routing path in packet-switched computer-communication networks.

Computer-communication networks over the past decade are outlined. A glossary of some of the terms used throughout this thesis are introduced. A brief description follows of the advantages of packet switching over the more conventional circuit-switched scheme for information transfer. The important design variables that a network planner is faced with in the design of these networks are discussed. A general design problem is stated and then decomposed into simpler subproblems one of which is the link-capacity assignment problem, which is briefly discussed. The route-assignment problem is identified as being of particular importance and is specified.

A network model is introduced and relationships between performance measures, input parameters and constraints that appear in the general design problem are discussed.

The routing problem is formulated and a heuristic routing procedure is suggested as a sub-optimum solution to the problem. Basic routing methods are discussed. The principles of datagram and virtual circuit techniques are explained with reference to the routing of packets throughout the network. The directory routing technique with alternate routing is identified as being a specific requirement and the operation of this technique is explained in more detail.

Two basic algorithms are introduced. The first which determines the shortest, second shortest, third shortest, etc., paths between all pairs of nodes in a network. The second which determines from all the paths in the first algorithm, the best alternative paths between all pairs of nodes in a network. A heuristic routing algorithm for establishing routing tables at each of the individual nodes in a packet switched data network is presented.

Among the properties of a desirable routing algorithm is that the paths established between all node pairs are such that the average packet delay from source to destination node is minimal. The heuristic-routing algorithm proposed is to be implemented on a newly proposed SAPONET packet-switching network, with special emphasis on the minimization of the average packet delay of the network. Results are presented and discussed for different combinations of the primary, secondary, tertiary and fourth alternative paths obtained. Finally results are summarized and areas for further work identified.

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CHAPTER 1
-----INTRODUCTION
-----1.1 BACKGROUND

The planning of large-scale fully integrated networks has stimulated the growth of a new discipline called computer communication analysis. This discipline involves problems similar to those arising in traffic, power and communications systems - in short in almost every kind of network structure.

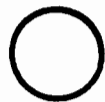
Development has been towards the establishment of a distributed computer network where computer resources and services that are geographically scattered can be connected to a high-capacity transmission grid forming a high-level network of resources. Users would gain access to this network of resources via a "low level" network of terminals and feeder lines. In this way the networking of physically remote computers offers a variety of new ways of enhancing data-processing capabilities. By means of such interconnections resources can be shared between participating processors, loads can be distributed and the operating reliability of each can be increased (1).

Computer communication networks have provided some of the most intricate challenges to network analysis and in turn have become one of its major beneficiaries.

During the past decade the need for data services has become increasingly evident - unfortunately the majority of common carrier plants today have been designed using voice communication objectives and as such exhibit many disadvantages to the data user. This is largely as a consequence of fundamental differences

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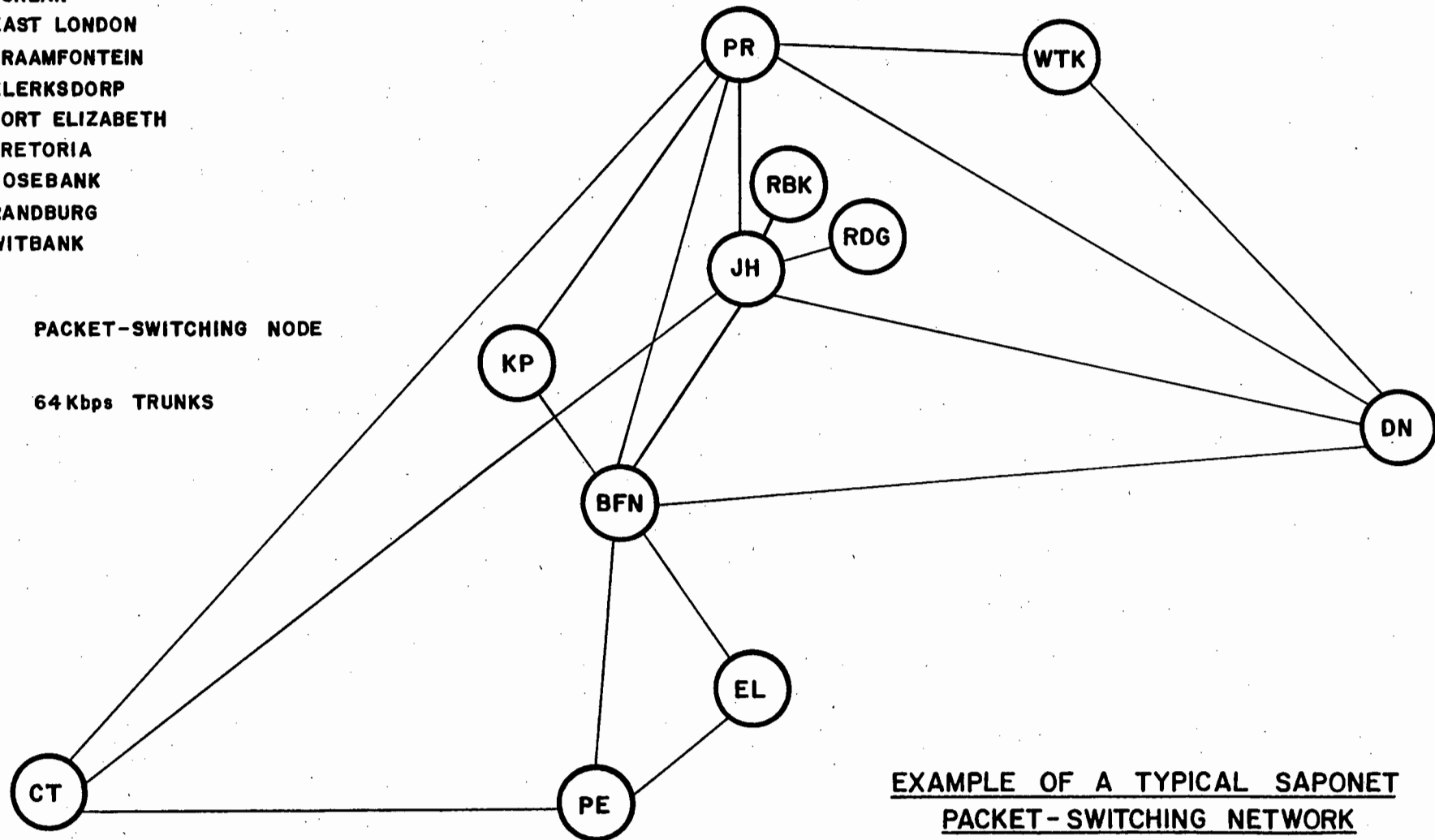
BFN BLOEMFONTEIN
CT CAPE TOWN
DN DURBAN
EL EAST LONDON
JH BRAAMFONTEIN
KP KLERKSDORP
PE PORT ELIZABETH
PR PRETORIA
RBK ROSEBANK
RDG RANDBURG
WTK WITBANK



PACKET-SWITCHING NODE



64 Kbps TRUNKS



**EXAMPLE OF A TYPICAL SAPONET
PACKET-SWITCHING NETWORK**

FIGURE 1

between voice and data traffic, namely, the telephone traffic is characterised by a low calling rate, long holding times, a narrow bandwidth of up to 4 KHz and insensitivity to line noise (2).

These disadvantages of the telephone network have, however, not prevented the commissioning of a number of public and private computer communication networks throughout the world today. ARPA-NET, TYMNET, GTE - Telenet of the USA and SITA (the International Airline Reservation Systems Network) are just a few examples of some of the resource-sharing networks that are in daily use. Multi-purpose public data networks have been set up by most P.T.T.'s (Post, Telegraph and Telephone Authority) such as British Telecom Packet Switched Stream Services (PSS), Brazil's REXPAC and South Africa's SAPONET-P.

The SAPONET computer communication network is shown in FIGURE 1.

1.1.1 Glossary of Terms

Due to the rapidly evolving nature of data-communications network technology, the terminology used is not always consistent. Herein the following terms are clarified:

Packet - a packet of information is a finite sequence of bits, divided into a control-header part and a data part. The header will contain enough information for the packet to be routed to its destination.

Node (data-switching exchange, packet switch, switching node) - the collection of hardware and software resources that implements all intranetwork procedures such as routing, resource allocation and error control and provides access to network packet-switching services through a host/network interface (the DCE or data-switching exchange in CCITT terminology).

Intermediate (transit) node - a node $j \neq s, t$ is called an intermediate node with respect to a packet of data with origin s and destination t if the path from s to t over which the packet is transmitted contains node j

Trunk (links, hops) - this constitutes a single data-communication circuit between adjacent nodes

Path - the collection of sequential communication links ultimately connecting the source to the destination node without any repeating nodes.

Weighted path length - this is the length of the path in kilometres, which includes the physical length of the path and a weighted length in kilometres used for each intermediate node and any other processing stages traversed between source and destination nodes.

Feasible path - a path between a source and destination node where the number of nodes in the path is dependent on the maximum number of hops input by the routing manager. In addition, if the path has more than three hops then its weighted length must be less than the maximum acceptable weighted path length input by the routing manager.

Network - a finite collection of nodes connected to each other by links

Centralized network - a network of nodes where computer resources are accumulated at a central node

Distributed network - a network of nodes where computer resources are distributed amongst the nodes

Users (subscribers) - the host computer or terminal equipment connected to the network (the DTE or data terminal equipment)

Access line - the connection of the subscriber to the node via a communication circuit terminating at a "port" on the node

Host - the collection of hardware and software that utilizes the basic packet-switching service to support end-to-end interprocess communications and user services

Terminals - a collection of hardware and possibly software, which may be as simple as a character-mode teletype or as complex as a full scale computer system. As terminals increase in capability the distinction between "host" and "terminal" may become a matter of nomenclature without technical substance.

Protocol - a set of communication conventions, indicating formats and procedures that allow two or more end points to communicate. The end points may be packet switches (nodes), hosts, terminals, file systems, etc.

Packet delay - the total time that a packet spends in the network

Virtual circuit - a logical channel between source and destination nodes in a packet-switched network

Datagram - a finite length packet of data together with host address information that can be exchanged in its entirety between hosts independent of all other datagrams sent through a packet-switched network

Route - a route is defined as one or more trunk lines between two specified nodes. It is also used to describe a succession of routes, e.g. when referring to a route between non-adjacent nodes. Two nodes can be connected by more than one route through different intermediate nodes.

Fixed routing - a technique whereby each node will use a predefined route for transmission to a given destination node.

Alternate routing - a technique where each node in the network has tables indicating the primary, secondary, etc. routes to a given destination node

Adaptive routing - a technique where each node in the network adapts the selection of routes to a given destination node, according to the node or link failures or delays currently experienced on each possible route

Computer network USERS share not only processing facilities but also communication facilities. In the following sections a brief description is given of the main switching techniques being used at present to enable information transfer between sender and receiver. It is also shown how packet switching has revolutionized data communications over the last decade by offering attractive advantages over the more conventional circuit-switched scheme.

1.1.2 Circuit Switching

In a circuit switched network a dedicated path is established between the sender and receiver and this path is then held for the duration of the call whether any data is being transmitted or not. Circuit switching is analogous to the common telephone call where a physical "copper" path is established all the way from the sender's telephone to the receiver's telephone.

1.1.3 Message Switching

In message switching no physical copper path is established in advance between the sender and receiver. Instead the sender's data terminal equipment (DTE) will transmit the full message to the network-switching node, the Data Switching Exchange (DSE), to which it is attached. The network-switching node would then store the message until it has been received in full after which it would

then examine the destination DTE's address that is attached to the message and attempt to forward the message to the next switching node en route to the destination. In this way the messages work their way through the network from link to link until they reach their destination. The principle used in message switching is known as store-and-forward.

1.1.4 Packet Switching

The principles of packet switching are essentially the same as message switching, however, the significant difference is that for the former messages are broken up into multiple packets.

A packet is regarded as a fixed maximum unit length of data and control information that is sent from source to destination. The packet is received by the switching node (DSE) from the USER and interleaved with other packets as they are routed through the network to their destination. The store-and-forward principle, as used in message switching, is adapted as the packet is transmitted across the network (2), (3), (4), (5).

Packet switching techniques have the advantage over message switching in that interactive traffic can be handled by ensuring that no user will monopolize any transmission line for more than a few tens of milliseconds.

Additionally it reduces delay and improves throughput by allowing the first packet received in a multipacket message to be forwarded to the next switching node en route to its destination before subsequent packets have fully arrived.

The key difference between circuit and packet switching is that in circuit switching the required bandwidth for a circuit is allocated beforehand whereas in packet switching the bandwidth is allocated as it is needed (3).

It has therefore been recognized that a fixed allocation of channel capacity as in circuit switching is regarded as extremely wasteful especially because of the interactive and sporadic nature of data traffic where short periods of activity are separated by long idle periods when no information is being transmitted. To quote Kleinrock and Lam (6) "rather than provide channels on a user-pair basis, we much prefer to provide a single high-speed channel to a large number of USERS which can be shared in some fashion; this allows us to take advantage of the powerful "large number laws" which state that with every high probability the demand at any instant will be approximately equal to the sum of the average demands of that population".

In designing a packet-switched computer communication network the following are some of the important factors that have to be considered.

1.1.4.1 Network Topology

The topology of a network simply refers to the geographical configuration of the network resources. It is by no means unique to packet-switched computer communication networks as for many years it has been intensively studied in relation to a wide range of transportation and communication problems such as in the design of conventional switching networks for voice communication (5).

A large-scale integrated computer communication network is a multilevel hierarchical structure consisting, in the main, of a backbone network (high level) and a local-access network (low speed) (7). The problem that normally faces a network planner is the optimization of the topology for the backbone and local-access networks.

Essentially the topological design problem of a computer communication network given the geographical location of terminals and potential message (data packet) sources as well as their expected traffic characteristics is to determine:

- (i) Where shall the concentrators and switching nodes (DSEs) be located?
- (ii) How should the nodes be interconnected?
- (iii) What form should the network take i.e. star, tree, loop, mesh etc?
- (iv) How many links (trunks) are required and what should their capacities be? (8).

In designing the optimum topology the designer has to consider constraints such as the reliability of the network and the delay through the network. Additionally, variables such as the capacity of the links and the flow of traffic have to be carefully considered. Finally the network designer has to achieve all these goals at minimal costs.

1.1.4.2 Line-capacity Allocation

Once the network topology has been specified it is then necessary to select the best allocation of capacities for each channel. This is basically the allocation of capacity, link by link, so as to minimize average packet time delay. It therefore involves the optimization of the size of trunks that should be used throughout the backbone network as well as optimizing the capacity of the links from the local to the backbone network.

In order to optimize the capacity allocation for a network one must be given the traffic flowing between centres or DSEs as well as the route assigned to packets entering the network at one city and destined for another (5), (8). Techniques that are adopted in the solution of the capacity assignment problem will also depend, to a large degree on the nature of the cost versus the capacity function.

1.1.4.3 Routing Procedures

Routing policies must be such that low delays for the subscribers of a packet network are consistently achieved. Factors such as changes in the network topology or changes in the traffic load between source and destination nodes must be accounted for. Additionally packets must be routed away from temporarily congested nodes within the network, that is, in cases where the arrival rates of the input traffic and the effective capacity of output trunks at a node are not matched.

In networks, such as ARPANET, with a large amount of nodes (greater than forty) dynamic routing algorithms are designed to ensure that packets do in fact find and use the shortest or lowest delay path through the network. In smaller networks, such as SAPONET, with less nodes the packets are normally routed through the network in accordance with a fixed routing decision (3), (5).

1.1.4.4 Flow-control Procedures

There must be smooth traffic flow throughout the network. The routing algorithm does effectively control the flow of traffic throughout the network, however, it has no control over the incoming data at the switching nodes. Bottlenecks and deadlocks have to be prevented and flow-control procedures are required to prevent any one customer's data source from monopolizing the network (8).

It can be appreciated that the solutions of the above-mentioned problems are extremely complex. However, several algorithms have been proposed to solve these problems and are available to the network designer (3), (5), (8), (9).

Reflecting the enthusiasm for challenging the new horizon of telecommunications as well as the diversified facets of computer communications technology, this thesis deals in particular with the route-assignment problem. In order to indicate how the routing problem was chosen as an area of research it is necessary to formulate the general design problem that faces prospective network designers of today's computer communication networks.

1.2 THE DESIGN PROBLEM

Several different formulations of the design problem can be found in the literature (7), (8), (9). Generally, they correspond to different choices of performance measures, of design variable and of constraints. The following is a very general formulation of the design problem according to reference 9.

Given	Node locations Peak-hour traffic requirements between node pairs
Minimize	The network's total average packet delay
Over the design variables	Topology Channel capacities Routing policy
Subject to	Link capacity constraints Network costs Reliability constraint

Three of the main subproblems facing the designer are the capacity assignment, the flow assignment and flow and capacity assignment problems that are basically derived from the above general formulation by fixing some of the design variables (9). An initial study was undertaken to investigate the problem of discrete link-capacity assignment in store-and-forward packet-switching communication networks. The location of the store-and-forward nodes, the average packet rate between each pair of nodes, the network topology and the routing of the packets were assumed to be known. The problem formulation called for the minimization of the total link cost D while satisfying all the average-packet delay constraints specified

by different users. $D = \sum_{i=1}^P d_i(C_i)$ where C_i is the discrete-link capacity of the i^{th} link and p is the number of links.

The algorithm theoretically developed but not implemented was based on the design criterion of minimizing the total link cost D proposed by Maruyama and Tang (10), (11), (12), which called for the following general formulation:

Given

The network topology and node locations
The traffic requirement matrix for each node pair

The routing policy and hence the flow assignment for each packet class (users with similar time delay requirements were grouped into different packet classes)

An average delay bound for each packet class.

Minimize

The total network cost with respect to the discrete link capacities

Subject to

Average packet-delay constraints for each packet class

As mentioned in section 1.1.4.2, as a stand-alone problem, the optimal assignment of capacities to a distributed computer communication network with fixed routes is not very interesting as the selection of the fixed routing policies plays a greater determining role in the optimization of the overall network performance. The capacity assignment problem is of practical interest as a subproblem of more general optimization problems (9) and for this reason and the requirement by SAPONET for a fixed set of routing tables for each node in the network, the direction of study was changed to investigate the more general problem of route assignment.

1.3 OBJECTIVE

The objective of route assignment can be defined as the optimal transfer of packets of data through a network when the traffic requirement between all nodes in the network and the network conditions are given. The criteria from a user's point of view may either be the minimization of average packet delay or the maximization of network utilization although many other performance criteria could be considered equally valid.

The aim of this thesis is to determine a fixed set of "optimum" routing tables for a packet-switched computer communication network where packets are routed, as a first choice, from source to destination nodes along their respective shortest paths, whereas the second, third, etc., choice paths do not necessary have to be the shortest paths. The shortest paths are defined as those paths between source and destination node with the least number of intermediate nodes (including least number of additional multiprocessing interconnections at the intermediate nodes) and shortest physical length. The objective throughout is that the average source to destination packet delay must be minimized subject to a set of flow constraints. The network employs a store-and-forward technique with data packets moving from a source to a destination, buffered at intermediate nodes along the path.

The network considered provides a total distributed-node data-communications network facility where a virtual-circuit technique is used between source and destination nodes. The distributed packet-switched data communication network is considered as a collection of nodes connected by full duplex links comprising the topology. The input traffic into the network is described by a matrix of rates and packets/second of traffic originating at one node and destined for another. The capacity of each link is fixed.

The routing algorithm, a heuristic algorithm for "sub-optimum" solutions to the routing problem, is to be a supervisory task, in the Network Control Center, containing the global information about the network (current topology, line capacity, condition of links and nodes, etc). Firstly, a network has to be considered and a routing procedure determined independent of traffic flows within the network, by assuming that for each message a path that contains the lowest weighted length and the fewest number of intermediate nodes from origin to destination is most desirable (the shortest path algorithm). A node must be selected as the initial source node and all paths containing the fewest number of intermediate nodes to all possible destination nodes in the network must be generated. A limit is placed on the number of intermediate nodes in a path and the total weighted length of the path that is defined by the routing manager. Such paths will be called feasible paths. The procedure must continue until all nodes within the network have been assigned their respective feasible paths. All feasible paths between each node pair within the network must then be arranged in ascending order of weighted length. The weighted length of each feasible path is measured in kilometres and is a function of the physical length of the path as well as a weighted variable (defined by the routing manager) for each intermediate node and any additional processor unit encountered in a path. Secondly, as a specific requirement for the SAPONET network, an algorithm must be developed to determine from all the feasible paths the best alternate paths between all pairs of nodes in the network. The best alternate paths being defined here as the path with the lowest

weighted path length and those paths with the next lowest weighted length that have an alternate "primary hop" (the first hop in a path) to any of the previous best alternate paths found between the same node pairs. Finally the best alternate paths for each node in the network have to be considered together with traffic flow information given and a routing procedure must be adopted to determine the primary paths between all source to destination pairs within the network. The primary paths represent the preferred choices for routing the call. In the case of a node or link failure the routing algorithm must then include secondary paths between all source to destination node pairs within the network, where these secondary paths represent alternate routes that are less optimal. In the case of two node or link failures within the network and where both the primary and secondary paths between node pairs are affected, the tertiary paths must be established by the routing algorithm. In those cases where more than two nodes or links fail within the network and where the primary, secondary and tertiary paths are all affected between certain node pairs fourth alternate paths must be established, where practically possible by the routing algorithm. All these paths selected have to be "optimized" with a view to minimizing the average packet delay along each path. The recommended fixed set of "optimal" primary, secondary and, where possible, tertiary and fourth alternate paths for each node in the network must then be tabulated for use by the Network Control Centre.

1.4 LITERATURE SURVEY

The literature used initially as source material for this thesis was that of the Packet Switching Network Architecture of the South African Post Office Switched Data Network (SAPONET). A sound understanding of the basic operation and interconnection of the network processors for the proposed network formed an initial basic requirement for all the work undertaken.

In chapter 3 the routing problem is formulated and a heuristic routing procedure is suggested as a sub-optimum solution to the problem. Basic routing methods are discussed. The principles of datagram and virtual-circuit techniques are explained with special reference to their respective routing operations. The directory routing technique with alternate routing is identified as being a specific requirement and the operation of this technique is detailed.

In chapter 4 two basic algorithms are introduced. The first determines, independent of traffic flows within the network, the shortest, second shortest, third shortest, etc., paths between all pairs of nodes in the network based on the number of hops in a path and the weighted-path length. These are the feasible paths. The second algorithm determines from all the feasible paths the best alternate paths between all pairs of nodes in the network. A heuristic routing algorithm for establishing routing tables at each of the individual nodes in a packet-switched data network is then presented. These tables are established by selecting the "optimum" best alternate paths for each node in the network and are dependent on traffic flows within the network.

Chapter 5 presents and discusses results obtained by simulating the heuristic routing algorithm on a newly proposed SAPONET packet-switched network.

In chapter 6 results are summarized and areas for further work identified.

The Appendices include some descriptive material on data-communication terminology and details of the algorithms used throughout this thesis as well as tabulated results.

CHAPTER 2

MODELLING AND ANALYSIS OF THE NETWORK

2.1 INTRODUCTION

The rapid progress in computer technology has provided the capability of communication processing to each node in the network, thereby contributing to the realization of a versatile distributed network. The characteristic of computer communications of permitting the use of store-and-forward techniques, as mentioned in chapter 1, has drastically improved usage of the communication links.

In-depth studies have therefore been directed towards the problems of queueing and network flows, in general, and more specifically to such problems as the delay analysis, topological design, flow control, route assignment etc. Many of these problems, however, fall into a category that has been impossible to solve rigorously. For example, the delay analysis of a tandem queue is only known if the service time is exponentially distributed. In reality, however, service time is almost constant when a message is divided into a sequence of message blocks or packets having a fixed size. The topological design of a practical network has to deal with a large number of parameters that make the analytical solution impossible.

From the above examples it is clear that some approximations must be used in almost all design cases and it may be said that the urgent needs for the design of computer communication networks enforce the use of bold approximations.

In this chapter a model of a packet-switched network is introduced and the relationship between performance measures, input parameters and constraints that appear in the general design problem, formulated in Chapter 1, are discussed as well as the approximations and assumptions that are stipulated. The average packet delay has been chosen as the measure of network performance and it is accordingly intended that the model, although idealized, exposes the fundamental behaviour of the average packet delay in store-and-forward networks.

It is important to mention at this point that most of the design methodology and terminology presented in this and the following chapters has been developed with the TRAN packet-switched network of the South African Post Office in mind, although the principles do extend to more general networks. Further details regarding the network architecture can be found in APPENDIX A.

2.2 THE MODEL

A computer-communication network model for performance analyses is considered where packets are transmitted through the network using a store-and-forward technique. The network consists of N nodes and P links with each node acting as a store-and-forward switching station (with infinite storage capacity) and each link is considered to be an error-free communication channel. Additionally it is assumed that packets originating at one node destined for another node arrive at random times according to Poisson's statistics. Finally, for simplicity a general packet-length distribution is assumed where the average packet length is 128 bytes (1024 bits/packet) based on statistics of average packet length obtained from the SAPONET packet-switched network.

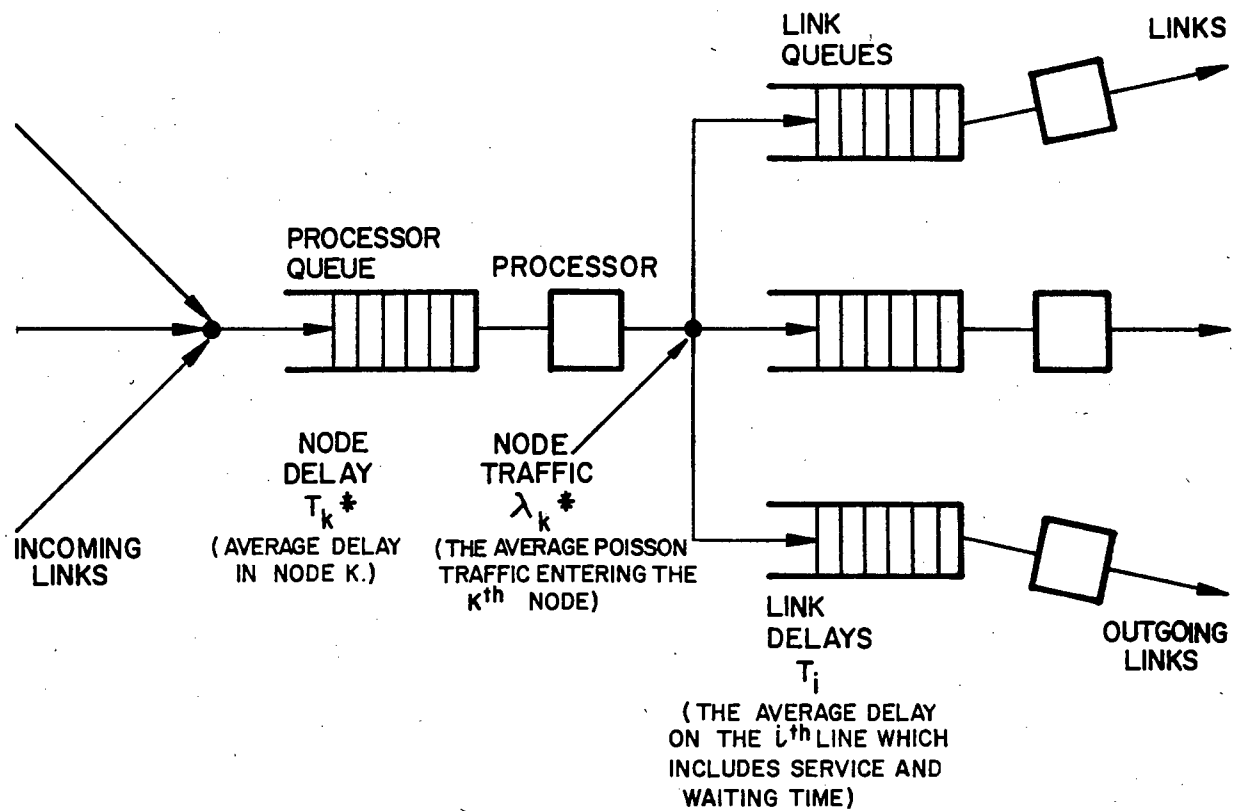
Several different algorithms that were proposed to solve the route assignment problem were found in the literature. Some of the algorithms were of the heuristic nature and others were based on more rigorous mathematical programming, queueing and network-flow concepts. In order to obtain a sound understanding of all possible solutions to the routing problem, whether optimum or sub-optimum, all these algorithms were studied in depth. The contributions of the authors aided in grasping the concepts behind the routing problem in question.

It is extremely difficult to isolate specific source documents as all the literature contributed in some way or another to the solution of the routing problem. However, the heuristic routing procedure proposed by H. Frank and W. Chou and the topological design techniques as proposed by M. Gerla and L. Kleinrock formed the fundamentals for the work undertaken here. The flow-deviation routing algorithm developed by L. Fratta, M. Gerla and L. Kleinrock, which provided an efficient optimal solution to the routing problem, was also studied in some depth.

Many of the authors who contributed to understanding the practical concepts behind the routing problem represented research teams who were concerned with the implementation of routing algorithms of similar interests. Their contribution proved valuable when forming an opinion as to the practical capabilities and limitations of the proposed routing algorithm.

1.5 OVERVIEW

In the next chapter a network model on which this study was based is introduced and relationships between performance measures, input parameters and constraints that appear in the general design problem are discussed. In setting up and solving the route-assignment problem, involvement in modelling, message input statistics and appropriate performance criteria is essential.



SIMPLIFIED MODEL OF A SWITCHING NODE

FIGURE 2

For the SAPONET model packet sizes of 32, 64, 128 and 256 bytes (256, 512, 1024 or 2048 bits/packet) could be selected. With these assumptions it is possible to model the packet-switching computer communication network as a stochastic network of queues in which each queue behaves as an independent M/M/1 queue (13), (14), (15). The validity of the above assumptions and approximations have been tested and verified through simulation and measurements by many authors in a variety of applications. The results indicate that the model is robust (8, 9).

2.3 AVERAGE TIME DELAY ANALYSIS

Computer networks can be ranked by the speed with which they service their USERS and in many systems the response time is the most crucial performance criterion (16). Network delay can be defined as the time taken for the USER to transfer his packet across the network from source to destination. It can be considered to contain two components namely, the time taken to establish a connection and the time then required to transport the data (2).

Factors that influence packet delay are the switching methods used, network traffic, high error rates, propagation delays and signalling speeds (2). When traffic is light, packet delay is primarily due to the time taken to store-and-forward packets at each switching node or if distances between source and destination node are long then propagation delay may also play a role. As traffic increases delays principally become a problem of queueing within each switching node, as shown in FIGURE 2 (a simplified model of a typical TRAN XPRO), (5), (14), (17).

Randomly, packets from the local access network arrive at the switching node where they are temporarily stored in the input queue. The arrival of these packets causes the queue

processor (data movement processor) to generate an interrupt via the memory bus to the main processor (packet level processor) after which it makes a decision on where to route the packet depending on information obtained from its routing tables. The packet is then forwarded to the appropriate output queue and if the line is available it would be duly transmitted. However, if the line is not available and a fixed routing technique is employed then the packet is stored in the output queue until such time as the line does become available. Where an adaptive routing technique is used it would be possible to dynamically reroute the packet over an alternate line that is not in use.

A very important factor is that the queue processor must be powerful enough (the throughput capacity of each XPRO is either 0,3 Mbps or 0,5 Mbps) to be able to process the incoming packets rapidly enough so as to ensure that the output line is not kept idle. If the output queue were to be emptied by the line while packets at the input queue were still waiting to be attended to by the processor there would be a great wastage of capacity on the output trunk (4), (5), (14).

Before proceeding with the section on communication costs, a number of definitions are necessary in order to obtain an expression for the average source to destination delay in the network. The letter i denotes a particular link where $1 \leq i \leq P$ (P is equal to the number of links in the network):

λ_i is the average traffic rate in packets per second on link i .

$1/\mu$ is the average packet length in bits per packet for the i th link (for the SAPONET model this value is assumed fixed at 1024 bits/packet for all links.)

- P_i is the average utilization factor of link i - the ratio of the average traffic flow on the i th link and the capacity of the i th link.
- T the average source to destination packet delay averaged over all nodes in the network.
- γ is the average total created traffic entering the network from external sources in packets per second.
- γ_{jk} is the average packet rate in packets per second flowing from source node j to destination node k .
- Z_{jk} is the average packet delay (queueing and transmission) in seconds from source node j to destination node k .
- C_i is the fixed capacity in bits per seconds for link i .
- T_i is the average delay for a packet passing through link i including both time in the queue and time in transmission.

From reference (9) the following relationships can be stated.

$$T = \sum_{\substack{j,k \\ j \neq k}} \frac{\gamma_{jk}}{\gamma} Z_{jk}$$

$$\gamma = \sum_{j,k} \gamma_{jk}$$

By applying Little's result (9), (14), (17) to the network-of-queues model leads to the following expression for the total average delay T , which is calculated by weighting each link delay T_i by the proportion of total traffic carried by it:

$$T = \sum_{i=1}^p \frac{\lambda_i}{\sum \lambda_i} T_i \dots\dots\dots 2.1$$

where p is the number of links in the network.

The load P_i on the i th link is namely the ratio of the average traffic flow on the i th link in bits per second and the capacity of the i th link i.e.

$$P_i = \frac{\lambda_i}{\mu C_i}$$

The average delay T_i on the i th line including service time per message T_s and the waiting time an information packet spends waiting at the message processor for link i to become available is (18).

$$T_i = \frac{T_s}{1 - P_i}$$

T_s is the average time taken to transmit an average information packet of length $1/\mu$ and therefore can be written as follows:

$$T_s = \frac{1}{\mu C_i}$$

Taking into consideration all the assumptions made in section 2.2, T_i can be rewritten as (9), (18), (19):

$$T_i = \frac{1}{\mu C_i - f_i} \dots\dots\dots 2.2$$

The average traffic rate f_i cannot in general be evaluated. However, if the assumptions mentioned in section 2.2 are taken into consideration and fixed routing tables and the traffic requirement matrix are given then f_i can be calculated (see section 2.5) analytically. By substituting (2.2) into (2.1) and letting f_i be the average bit rate on channel i in bits per second, the following expression for T is obtained:

$$T = \frac{1}{\mu} \sum_{i=1}^p \frac{f_i}{C_i - f_i} \dots\dots\dots 2.3$$

Where

$$f_i = \frac{\lambda_i}{\mu}$$

This delay expression is sufficiently accurate for most design purposes. However, it is possible as shown by Kleinrock (14), (15) to obtain expressions, which include propagation and nodal processing delays that correspond more accurately to measured results.

In this study the following formula has been used for T, which includes propagation and nodal processing delays.

$$T = \frac{1}{\gamma} \sum_{i=1}^p \lambda_i [T_i + P_{di} + NP_{di}] \dots\dots\dots 2.4$$

Where

P_{di} is the propagation delay on link i in seconds and is a function of the physical length of the link

NP_{di} is the nodal processing delay in seconds experienced at each switching node traversed by a message travelling from source to destination node

2.4 COMMUNICATION COSTS

The cost of a computer communication network does not only depend on the number of link connections in a network, but also on the length and capacity of these link connections. The link connections are those links between the local access network and the backbone network as well as the trunk links interconnecting the backbone switching nodes.

We can therefore say that the total costs of transmitting data from a source to a destination node consists of three basic components, namely the cost of (a) transmitting the data packets from the local-access network to the nearest switching node (b) processing carried out by the switching node and (c) transmitting the data packets over the nationwide transmission grid. As far as present-day computer and

This can be achieved by taking the distribution of traffic flow and estimating the traffic among the locations according to the USER traffic density in the vicinity of each switching node. This in effect creates an $N \times N$ (where N is the number of nodes in the network) traffic-flow matrix defining the traffic requirement from each node in the network to each of the other nodes in the network.

A traffic matrix $R = r(i,j)$ is specified where the ij entry in this matrix describes the average number of packets generated per second that have node i as the source and node j as the destination (3), (5), (15).

2.6 LINK FLOWS

The routing policy and traffic requirement matrix uniquely determine the vector $\underline{f} = (f_1, f_2, f_3, \dots, f_p)$ where f_i is the average data flow on link i (9).

By employing a fixed routing scheme (see chapter 3 for details) $\underline{f}$ can be evaluated as long as the following constraints are met (16):

- (1) The "flow conservation constraint" which requires that the flow into any node is equal to the flow out of that node. This can be expressed by the following equation:

$$\sum_j A_{ji} = \sum_k r_{ik} \quad \text{for } i = 1, 2, \dots, N \quad \dots\dots\dots 2.5$$

where

vector $\underline{f_i}$ whose j th component $f_{j,i}$ represents the flow in bits per second on the j th link destined for node i .

vector $\underline{r_i}$ whose j th entry $r_{j,i}$ is the flow rate in bits per second required from node j to node i for $j \neq i$ and the negative of the total traffic required at node i for node $j \neq i$.

the matrix A is the "nodal incidence matrix" of the network, i.e. if $a_{i,j} = 1$ then link j is direct out of node i and if $a_{i,j} = 0$ then link j is not incident at node i .

Thus, a typical member of a set of equations for (2.5) is an equation which states that the flow requirement from node k to node i , that is, $r_{k,i}$ must be equal to the difference of the total flow destined for node i that leaves node k and the total flow destined for node i that arrives at node k . This can be written as follows (16):

$$\sum_{j=1}^N a_{k,j} f_{j,i} = r_{k,i}$$

- (2) The flow on any link is equal to the sum of all commodities (packets of data being transmitted through the network) on that link, which can be expressed by the following expression:

$$\sum_{j=1}^N f_{j,i} - f_j = 0 \text{ for } j = 1, 2, \dots, N \dots 2.6$$

where

f_j is the total flow on link j .

$f_{j,i}$ is the flow on the j th link destined for node i .

If vector $\underline{f}$ does correspond to a realizable routing policy and requirement matrix, it conforms with constraints 2.5 and 2.6, then $\underline{f}$ is a multicommodity (MC) flow for the particular requirement matrix R . Further explanation and definitions of the multicommodity flow problem are given in APPENDIX B.

2.7 THE CAPACITY CONSTRAINT

It is necessary to select the capacities for each link with a view to minimizing the average packet time delay. The capacities of links interconnecting switching nodes are specified. However, there is an obvious constraint in that the link flow f_i cannot exceed the capacity C_i , which can be expressed by the following equation:

$$\underline{f} < \underline{c} \dots\dots\dots 2.7$$

where

vector $\underline{c}$ is the capacity vector the j th component of which is equal to the capacity C_j of the j th link in bits per second.

vector $\underline{f}$ is the flow vector the j th component f_j of which is equal to the total flow on the j th link in bits per second.

Considering delay expression 2.3 it can be seen that if the link flow approaches the link capacity the delay approaches infinity. Therefore if both capacity and delay constraints must be satisfied, the capacity constraint is implied by the delay constraint and can be disregarded (9).

2.8 RELIABILITY

Some ideas from graph theory are useful when studying the reliability of a network, so to begin with a short introduction to graph theory is given in APPENDIX C.

A factor of major importance to the successful operation of data-communication networks is their reliability and it is becoming increasingly significant as networks grow in size. Network reliability as distinguished from component or element reliability is mainly concerned with the dependence of the reliability of the network on the reliability of its nodes and links and the correct allocation of alternative paths in the event of node or link failures (20), (21).

Many designers believe that if there are at least two totally independent routes between all pairs of nodes, high network reliability would be maintained. Indeed, in the design of the initial ARPANET network the design procedure controlled reliability by insisting that there would be at least two node disjoint paths between every pair of nodes. Computation proved that for small ARPANET (less than forty nodes) this implied almost perfect reliability in the following sense:

Suppose node i in the network is inoperative a fraction p_i of the time for $i = 1, \dots, N$ (where N is equal to the number of nodes in the network) then a lower bound for the expected number of node pairs that cannot communicate is

equal to the expected number of node pairs not communicating in a network where every possible pair of nodes is joined by an invulnerable link. No addition or redistribution of links in any actual network can reduce the expected number of node pairs not communicating below this value. In smaller networks it is therefore accepted that the existence of two disjoint paths between each pair of nodes invariably results in an expected number of node pairs not communicating very near the lower bound and therefore the addition of more links for reliability purposes is not justified (21).

As the distributed network increases in size more than two connectivity must be provided to guarantee high reliability.

Additionally reliability can be improved by -

- 1) installing low-speed lines (and hence low cost lines) to provide additional connectivity for the local access network (between terminals and DSE's); and
- 2) installation of low cost, high throughput "bypass switches" at the DSE's. In the event of a DSE failure, flow would be directly routed from one high speed line onto another at the affected DSE and thus, a message path between neighbouring nodes (DSE's) is preserved.

Several other reliability measures have been proposed for computer communication networks (3), (8) but for this study a two connectivity (two node disjoint paths) between every pair of nodes is proposed to ensure a high probability rerouting capability in the event of a line or node failure and it is therefore assumed that this measure has been included as a constraint in the topological design of the network.

CHAPTER 3
-----THE ROUTING PROBLEM
-----3.1 INTRODUCTION

An efficient routing algorithm forms an essential part of a packet-switched data communication network and the efficiency of any network design depends crucially on the routing procedures used in operating the network (16). In packet switching each data packet carries within the packet header an indication of the virtual circuit the packet must use in order to reach the destination node. This indication is used by all nodes through which the packet passes, to decide on which link the packet must be transmitted to next. The objective of this decision process, which is expressed in the form of routing tables at each node, is to optimally transfer packets through the network from source to destination. The main criteria is to minimize the average packet delay, or to maximize the path bandwidth. The routing algorithm must additionally contribute to network reliability and provide some means of overcoming the effects of node or link failures by allowing alternative routes to be used (13), (22).

The route assignment may be made using a number of different methods and various implementations for each method. In the SAPONET network, for example, a directory routing technique is utilized where there is

a built-in alternate routing capability at each switching node (DSE), which defines the best route and up to seven alternate routes to a given remote node. The routing procedure of the existing TRAN 4410 network processor system employed by SAPONET is such that up to seven alternate routes may be defined between any pair of up to 32 nodes. Tandem paths between nodes may pass through up to three intermediate nodes. A priority value is assigned to each route, allowing the preferred routes to take priority over other routes when they are available. The built-in alternate routing capability allows service in the event of a circuit failure between nodes.

Before discussing the directory and other routing schemes, the problem of establishing a fix set of routing tables in a network utilizing the directory routing technique with alternate routing is formulated with the view of providing a better routing procedure to that of the existing TRAN system.

3.2 PROBLEM FORMULATION

Several different formulations of the routing problem can be found in the literature (3), (5), (9), (13) whereas in this study the problem is defined as that of finding a fixed-directory routing policy, including alternate routing for a virtual-circuit packet-switched data-communication network such that the total average packet time delay T of the network is minimized subject to a set of flow requirements. The routing procedure must be determined by assuming that for each message, the first choice path, which conforms with the following is most desirable:

- (i) the path which contains the least number of intermediate nodes.
- (ii) the path which contains the least number of additional multiprocessing interconnections at the intermediate nodes.
- (iii) the path with the lowest physical length.

However, when determining the alternate (second, third, etc.) paths, the routing procedure need not only select the shortest paths. Other possibilities must be considered with the view of ensuring that any set of routing tables recommended will provide the best average time delay that a data packet will spend within the network. A virtual-circuit orientated protocol with single-path routing per virtual circuit is used and the paths selected remain fixed for the duration of operation of the virtual circuit unless a failure occurs.

In the context of this study, the routing problem is divided into three phases. The first, which is necessary in order to provide input data to the problem defined above, determines all the feasible paths between all node pairs within the network by utilizing the shortest path algorithm - section 3.7 details how packets of data are routed over links using the shortest path. Secondly, the best alternative path algorithm selects, from all the feasible paths, the "lowest weighted" length paths between all node pairs in the network. The weight of a path between each source to destination node is determined by the physical length of the path, the number of intermediate nodes and number of XPRO's traversed along the path and is independent of traffic flow within the network. An example of how a path is "weighted" is shown in FIGURE 4(g). An additional requirement stipulated for the SAPONET model is that the best alternate paths must contain those paths with the "lowest weighted" path lengths and those paths with the next lowest weighted path length that have an alternate

"primary hop" to any of the previous best alternative paths found between the same node pair. If a feasible path contains the links $(i_0, i_1), (i_1, i_2), \dots, (i_{k-1}, i_k)$ where i_0 is the source node and i_k the destination node then (i_0, i_1) is defined as the "primary hop". Finally, a heuristic routing algorithm is used to select from the best alternate paths found, an "optimal" fixed routing table for each node in the network. The heuristic routing procedure requires each message to use a path that has the lowest weighted path length from origin to destination with a minimum average delay from message inception to arrival as the objective function and the conservation of flow and capacity limitations as the constraints.

Using the model detailed in Chapter 2 and given the following basic information:

- (i) The network topology with node locations
- (ii) The capacities of each link in the network C_i , where i is the i th link in the network
- (iii) The traffic requirement matrix R_{ij} , where r_{ij} entry of the matrix represents the traffic flow in packets per second between source node i and destination node j , the routing problem can be generally formulated as follows:

Minimize : The total average time delay of the network

$$T = \frac{1}{\gamma} \sum_{i=1}^p f_i \left[\frac{1}{(C_i - f_i)} + \mu(PD_i + NPD_i) \right] \quad \dots 3.1$$

Over the design variable: $\underline{f}=(f_1, f_2, \dots, f_p)$ where p is the number of links in the network ($P=\text{no of links times two for bothway unsymmetrical traffic}$).

Subject to:

- a) $\underline{f}$ is a multicommodity flow satisfying the requirement matrix R .
- b) $\underline{f} < \underline{C}$

The objective that the delay expression given in 3.1 must be minimized subject to a set of flow and capacity constraints makes the routing problem a convex multicommodity flow problem (26). The expression to be minimized in 3.1 is the sum of a set of convex functions where each term in the sum can be approximated by straight line segments and can be readily approached as a separable convex programming

problem with the delay as the objective function and the conservation of flow and capacity as the constraints. Therefore a unique local minimum, which is also the global minimum, can be found by using downhill search techniques (9), (13). A new downhill search algorithm, which finds the optimal solution called the flow deviation (FD) algorithm has been developed by L. Fratta, M. Gerla and L. Kleinrock and is given in APPENDIX D. The non-bifurcated algorithm was run at various traffic inputs and results (FIGURE 7) certainly showed that at the higher traffic input, paths selected by this algorithm were superior to those chosen by the heuristic approach. The algorithm developed (36), however only provided a solution for determining primary paths.

Several other optimal techniques for the solution of the M.C. flow problem can be found in the literature (9), (13), (26). However, their direct application to the routing problem generally proves to be rather cumbersome and computationally inefficient and consequently considerable effort has been made in developing suboptimal routing techniques.

H. Frank and W. Chou (16, 26) proposed a heuristic approach in which the routing strategy requires each message to use a path which contains the fewest number of intermediate nodes from origin to destination. In the procedure, link capacities are preassigned. Traffic is first routed from source node i to destination node j , which is directly connected to i , over link (i,j) . Consequently, after this stage, some flows will be assigned to the network. Each node connected to i by minimum node paths with one intermediate node is then considered. For any node j in this group, all feasible paths from i to j are examined, and the functions of the flow thus far assigned to each link and the preassigned capacity for this flow are evaluated. The paths which have minimum "resistance" to additional flow are selected. From the subset of paths thus selected, the path whose total physical length is minimum is then chosen and all traffic originating at i and destined for j is routed over this path. The fact that this routing procedure makes full use of available line capacities can be interpreted as minimizing the average delay from message inception to arrival subject to a set of flow requirements. This the basic heuristic algorithm is detailed in chapter 4.

In this study the above proposal by H. Frank and W. Chou has been followed with a number of variations and modifications as detailed in the following chapter. The main objective is to improve on the minimum average packet time delay obtained when implementing the heuristic procedure proposed by H. Frank and W. Chou.

3.3 Directory Routing

Sometimes referred to as "deterministic" routing, directory routing ensures that every packet flowing between a particular source and destination node will follow the route designated by the routing table or directory. The routes between all possible sources to destination node pairs are usually set up in accordance with certain criteria such as the shortest path, the maximum bandwidth path or the minimum estimated time-delay path etc. and these paths are then faithfully followed unless the routing directory is changed by the operators or the network control centre.

The major disadvantage of the directory-routing technique is that it is highly structured and unable to adapt dynamically to changes in the network configuration or operation as a result of line or node failures or severe load fluctuations (5), (23).

3.4 Adaptive Routing

The adaptive-routing method attempts to capture the advantages of the directory routing method while eliminating its disadvantages (5). Each node in the network has a routing table in its memory that indicates the best route in real time for all destination nodes within the network. This routing table will change, depending on any change in the network operating conditions such as load fluctuations, node or link failures, etc. The current entries in the routing tables effectively represent, in real time, the best possible route to all destination nodes.

The major disadvantage of this routing technique is the complexity of forming the routing matrix formulation for each node in the network in real time and since the routing is neither deterministic (fixed directory), nor highly robust (flooding method) problems in the routing could cause failure in the network's ability to deliver user traffic properly (5).

It has also been shown that at steady state, flow patterns and delays induced by good adaptive routing schemes are very close to those obtained with optimal fixed policies. This fact is sufficient to suggest that network configurations configured with fixed routing are also near optimal for adaptive routing operations, provided steady-state conditions prevail and there are no regular node or link failures within the network (9).

Consequently, for these reasons and the fact that the South African Post Office is presently concerned with the design of smaller networks (less than forty nodes), the routing scheme required by SAPO is such that it should respond to a failing trunk or trunks according to tables set up at the switching nodes that mainly involves clearing all calls on the affected trunk and providing an alternate path between the affected sources and destination nodes (24). Since the type of technique, i.e. whether virtual circuit or datagrams, implemented by a packet-switching network has a major influence on the routing technique available, it is necessary to clearly define the two techniques.

Packets of data do not necessarily have to follow the same route across a network and therefore messages could arrive at their respective destinations out of sequence. There are two distinct solutions to this problem. The first is to carry sequence information with the packets and allow the destination to reassemble the message - this is a datagram protocol. The second is to force all packets to follow the same route in much the same way as they would on

a circuit switched path - this is a virtual-circuit protocol.

In the following sections the principles of datagram and virtual circuits are discussed.

3.5 PRINCIPLES OF DATAGRAM PACKET-SWITCHED NETWORKS

Datagram networks are effectively message-switched networks with a fixed maximum packet length. Alternatively from a user point of view they can be viewed as packet-switched networks, where the network-level protocol effectively only offers one service - namely to accept a packet of data from the user and to deliver that packet to the destination specified by the user in an address sent with the data.

No call set-up procedure is possible so it is up to the user to check whether the called party is available.

The network neither guarantees to deliver the packet nor provide any confirmation of delivery and it is left to the user to ensure end-to-end acknowledgement. Using the X.25 datagram protocol as an example (39, 40), the network will send a non-delivery message if it knows that the packet has been lost and, if the user requests the facility, the network will send him a delivery confirmation for every packet safely delivered. These return messages are called Datagram Service Signals. However, there is no guarantee that the Datagram Service Signals will not be lost in the network, for example, if the node in which they are being stored in transit should fail. It is thus up to the user to set timeouts to ensure the safe delivery of a packet.

It is also up to the user to identify the packets he sends into the network. This identification is not only required for delivery confirmation, but also to ensure that the receiving user can reassemble the arriving packets in the order they were sent.

From a routing point of view datagram networks have an inherent reliability that is not possible in circuit switched or virtual-circuit packet-switched networks. Since there is no fixed path through the network, failure of a node or trunk does not necessarily affect message transmission. Datagrams can simply be routed round the failed portion of the network (2,35). Another important aspect of a datagram network is that there is no call set-up delay as experienced in a virtual circuit protocol. Messages that can be fitted into a single packet provide a considerable advantage with regard to overall delay performance. Finally, transmission delay in any network becomes critical under heavy traffic conditions since packets are delayed at each node while waiting for bandwidth to become available. In a datagram network, as in the case of node or link failures, it is also possible under heavy traffic conditions to continuously update the routing tables of each node to enable the packets to be diverted from ports of the network that are congested.

3.6 PRINCIPLES OF VIRTUAL-CIRCUIT PACKET-SWITCHED NETWORKS

Virtual-circuit (VC) packet-switched networks are an attempt to make a packet-switched network appear to the user as being similar to a circuit-switched network.

In order to establish a virtual-circuit communication with another user, a DTE must go through a call set-up phase, just as for circuit switching. However, the manner of call set up differs from circuit switching in that the user sets

up the call by sending a "call request" packet to the network access node. This node uses its routing tables to direct the call-request packet to the next node on the path towards the destination. This is repeated until the packet reaches the destination node.

Should equipment fail along the path of the virtual circuit the call must be cleared and it is up to the user to re-establish it (2,35).

Inside the network the main trade-off between virtual circuits and datagrams is between the packet-switch (DCE) memory space and bandwidth. Since routing decisions are made only once a new virtual circuit is being set up within the network, both these factors would significantly influence the overall time that a packet spends within the network. Additionally, if a packet switch goes down and loses its memory, even if it comes back up a second later, all the virtual circuits passing through it will have to be aborted and an alternate route chosen with new virtual circuits being set-up. In contrast, if a datagram packet switch goes down, only those users whose packets were queued up in the packet switch at the time will suffer, and maybe not even all those depending upon whether they have already been acknowledged or not. The loss of a communication line is fatal to the virtual circuits using it as all these virtual circuits would again be aborted and reinitiated. However, datagrams can be easily compensated since the packet switches can balance the traffic throughout the network and routes can be changed halfway through a conversation. Generally from a routing point of view, in the virtual circuit case, the routing algorithm used within the network can certainly guarantee optimal transfer of packets from source to destination node under normal operating conditions. The average time that packets spend within the network invariably would be no worse or better than equivalent packets using a datagram protocol. However, under link or node failure conditions packets routed within a

network using the datagram protocol have a definite advantage over those employing the virtual-circuit technique.

A variation of virtual-call service, known as the fast-select facility, provides for the exchange of up to 128 octets of data during the call-establishment and clearing procedures for virtual-circuit calls. Fast select effectively extends the capability of virtual call service to satisfy more transaction-oriented applications where at least one inquiry and one response is needed for a communication.

When the fast-select facility is activated for a virtual call, the call-request packets contains a "facility request", indicating fast-select with one of two possible parameters. The parameters indicate whether there is a restriction on the response allowed to the incoming call at the destination.

The fast-select call without restriction to response processes the call-request packet and delivers the maximum 128 octet call user-data field to the destination in the incoming call packet. The destination either responds with a call accepted packet or a clear request packet containing up to 128 octets of user data. If a call accepted packet is sent, the maximum 128 octets of data are delivered to the call originator in a call connected packet. Subsequent packets during the remainder of the call are processed for normal virtual-call service. In effect, fast-select accelerates the virtual call process in establishing a communication. Additionally, inquiry response applications can be more efficiently satisfied (39).

While routing procedures can be set up within a network more or less independently of the protocols seen by the users, the choice of an appropriate routing procedure is influenced to some extent by the transport protocols (virtual circuit or datagram) operating at the network/user interface.

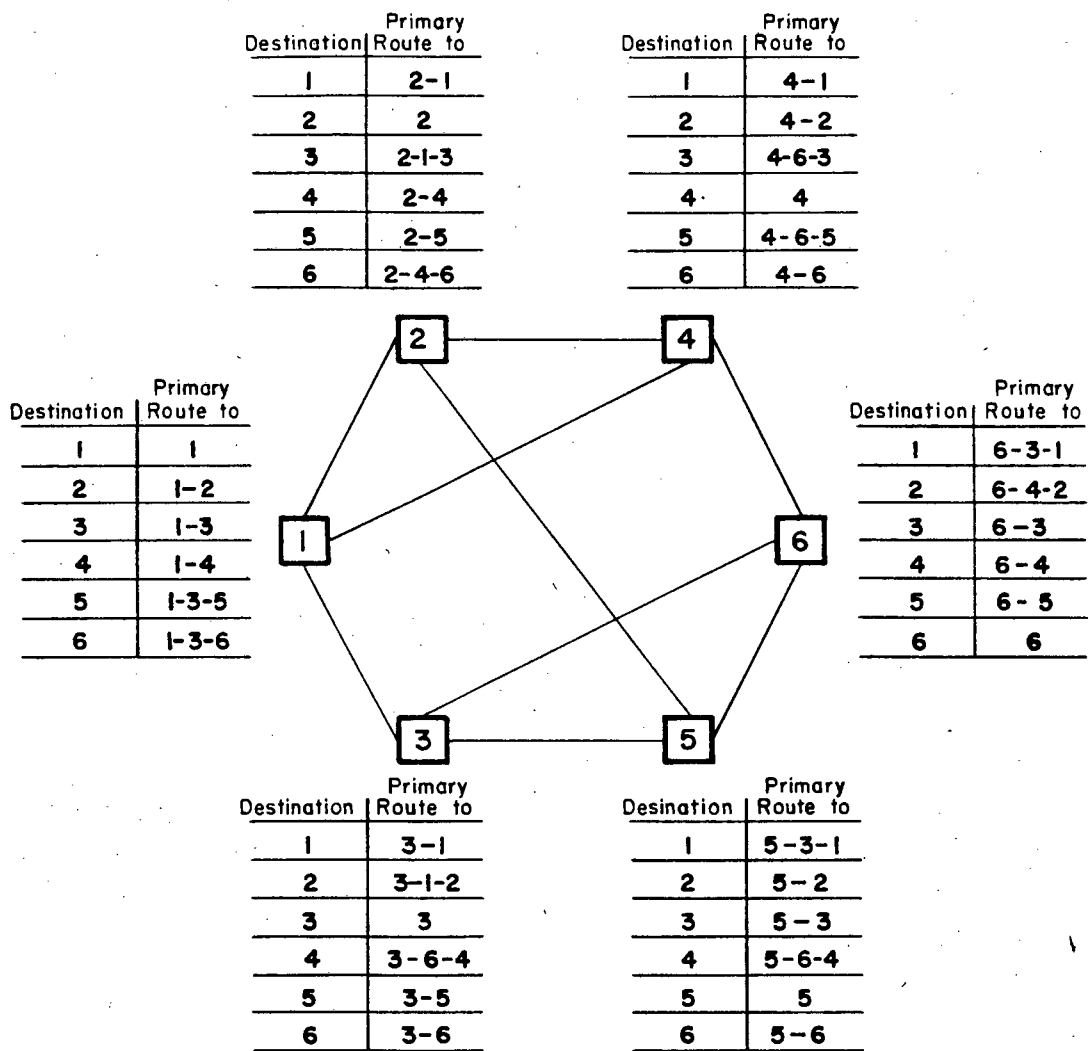
ARPANET and the Digital Equipment Corporation (DEC) network architecture, known as DECNET, are examples of users of the datagram network-layer protocol. ARPANET uses the "flooding-routing" technique to forward to all the nodes in the network any information regarding changes in link time delays. SAPONET and SNA are examples of users of the virtual-circuit network-layer protocol whereas DATAPAC have a hybrid solution where the network access is based on a virtual-circuit protocol and the internal protocol uses the datagram technique.

In the following section further explanation and operation of the directory routing scheme with alternative routing is given for a virtual circuit packet switched network similar to that used in SAPONET.

3.7 DIRECTORY ROUTING TECHNIQUE WITH ALTERNATE ROUTING

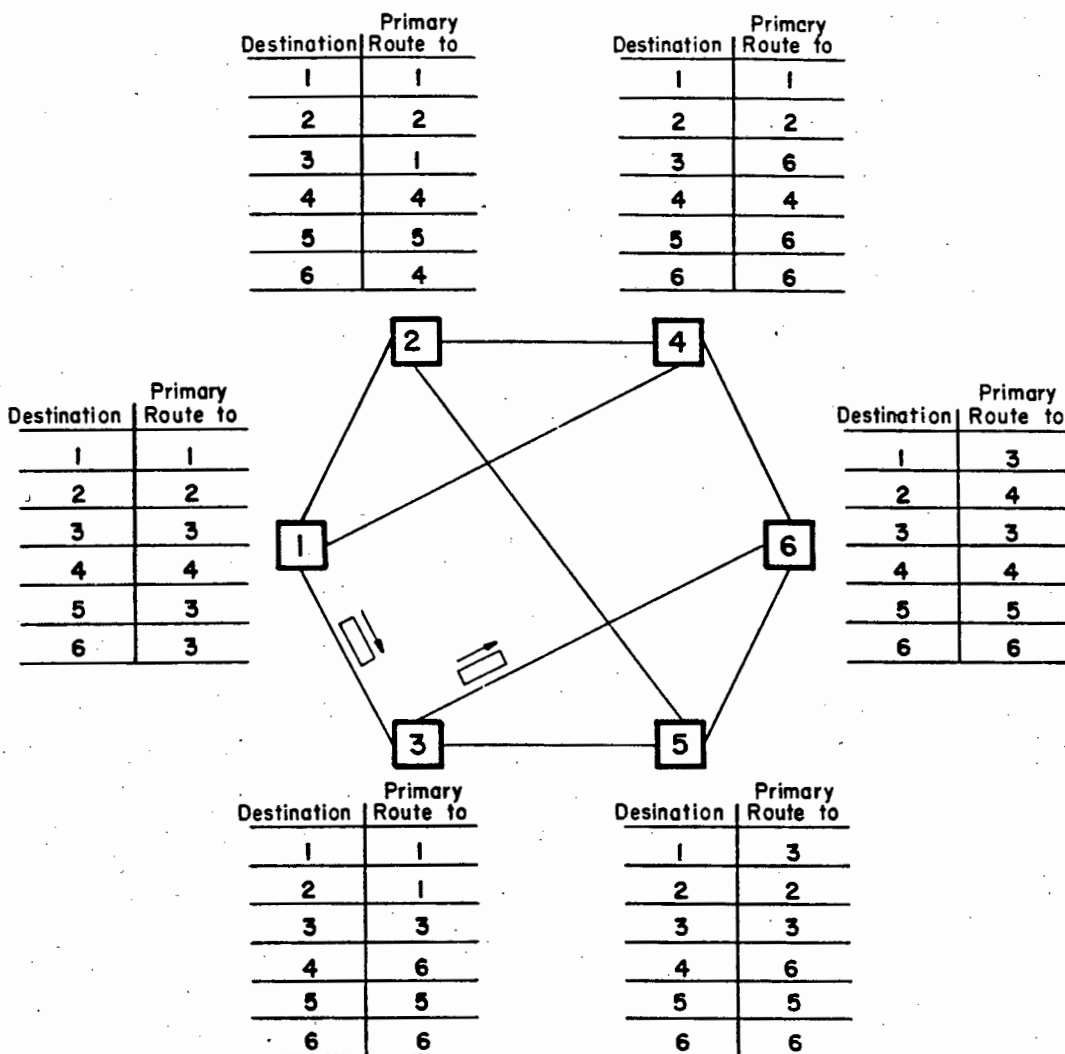
To operate reliably, directory routing has to include not only the primary choice path, but also secondary, tertiary, etc. choices to use under specified conditions such as line failures, known switch failures or severe traffic overloads (5). As the problem formulation detailed in 3.5 calls for a fixed directory routing scheme, a sample network shown in FIGURE 3(a) will be used to explain how the network operates under control of directory-routing tables. The primary path routing matrix containing 36 entries for a six-node network is shown in FIGURE 3(c). Each entry in the matrix shows the next node along the shortest path (the path with the minimum amount of intermediate nodes) in this case, from any node to any other node in the network.

For example, packets going to node 2 that are presently at node 6 should be routed to node 4 next. Each node in the network has its primary route tabled (see FIGURE 3(a)). Although the full paths are shown in FIGURE 3(a) only the



SAMPLE NETWORK USING DIRECTORY ROUTING TECHNIQUE WITH
ONLY THE PRIMARY ROUTES GIVEN FOR EACH SWITCH

FIGURE 3(a)



MODIFIED SAMPLE NETWORK SHOWN IN 5(a) WITH ONLY THE NECESSARY INFORMATION REQUIRED AT EACH SWITCH

FIGURE 3(b)

	TO NODE					
	1	2	3	4	5	6
FROM NODE	1	-	2	3	4	3
	2	1	-	1	4	5
	3	1	1	-	6	5
	4	1	2	6	-	6
	5	3	2	3	6	-
	6	3	4	3	4	5

PRIMARY PATH ROUTING MATRIX

FIGURE 3 (c)

single row of the routing matrix relating to a particular switch (DSE) needs to be stored at each switch. FIGURE 3(b), shows the same network shown in 3(a) illustrating the local routing table for each switch, which simply shows for each possible destination node, the proper node to which a packet should be routed next. The local routing table is identical to the horizontal row corresponding to that node in the overall routing matrix (5). Similarly each node's secondary and tertiary paths can be tabled and their respective routing matrices formed.

For a packet flowing from node 1 to node 6, the node 1 routing table indicates that one should send the packet to node 3. When the packet reaches node 3, the local routing indicates that packets destined for node 6 should be routed to node 6 directly.

If the secondary path choice between node 1 and node 6 was 1 - 4 - 6 then, in the case of a link failure, say the link between node 1 and 3, the packet would be sent on its secondary path from node 1 to node 4. At node 4 the local routing table would indicate that packets destined for node 6 should be routed to node 6 directly. Additionally it is important to note that in the case of a link failure between node 1 and node 3, as explained previously, only node 1 and node 3 are aware of this failure. Traffic between any source and destination node that uses this link will be rerouted via the second choice route at node 1 and 3 respectively and in such a way that they do not loop back on the incoming link they used in order to get to these nodes. The routing tables at the nodes would have to be updated by the Network Control Centre until the link is restored.

Considering the link-failure conditions explained above, there are other possible paths that the data packet could take in order to go from node 1 to node 6, one of which is path 1-2-4-6. This path may be physically longer than path 1-4-6 but it could guarantee that under heavy traffic loads, the data packet would be routed away from the heavily loaded links. Since the routing technique does not adapt dynamically to line or node failures, the question which the network designer must ask is: "has the optimum combination of alternative paths been chosen for the network under link failure conditions?"

CHAPTER 4

THE ROUTING ALGORITHMS

4.1 INTRODUCTION

The total traffic flowing in a computer communication network consists of three main factors (16):

- (1) The total traffic entering the network
- (2) The number of links in the path chosen for routing
- (3) Overheads such as headers, acknowledgements, parity checks, etc.

The most important factors are (1) and (2) as they contribute the majority of the traffic flow within the network. Suppose, for example, that one were to transmit 10 000 bits per second of data from node i to node j. If there is a direct path between nodes i and j then one would be adding 10 000 bits per second of data to the flow within the network. However if one were required to go to node j from node i via intermediate (transit) nodes k and l then we would be adding 10 000 bits per second of data between nodes i and k, 10 000 bits per second of data between nodes k and l, and 10 000 bits per second of data between nodes l and j, which is effectively adding 30 000 bits per second of data to the total flow within the network.

Whenever possible, flows should be routed over paths with as few intermediate nodes as possible; the heuristic routing algorithms as proposed by H. Frank and W. Chou do follow this principle (16), (26).

In the following section the basic heuristic algorithm proposed by H. Frank and W. Chou is detailed as per reference (16), (26).

4.2 BASIC HEURISTIC ALGORITHM

Given : A proposed network topology

The required traffic matrix

Routes are determined as follows: For each i
($i = 1, 2, \dots, N$):

(1) With node i as an initial node, a labelling procedure (27) is used to generate all paths containing the fewest number of intermediate nodes, to all nodes which have non-zero traffic from node i . Such paths are called feasible paths.

(2) If node i has non-zero traffic to node j ($j = 1, 2, \dots, N, j \neq i$) and the feasible paths from i to j contains more than NMAX intermediate nodes, then the topology is considered infeasible.

(3) Nodes are grouped as follows:

- (i) All nodes connected to node i
- (ii) All nodes connected to node i by a feasible path with one intermediate node.
- .
- .
- .
- (K) All nodes connected to node i by a feasible path with $K-1$ intermediate nodes.
- .
- .
- .
- (NMAX-1) All nodes connected to node i by a feasible path with NMAX-2 intermediate nodes.

Traffic is first routed from node i to any node j which is directly connected to i over link (i, j) , where (i, j) represent the link connecting node i and node j . Consequently, after this stage, some flows will be assigned to the network. Each node in each group is then considered:

For any node j in a group, all feasible paths from i to j are examined, and functions of the flow thus far assigned to each link and the required capacity for this flow are evaluated. The maximum flow thus far assigned in any link in each path is found. All paths which have minimum resistance to additional flow are then selected (paths whose maximum path flow are minimum, paths with the largest minimum residual capacity or paths with the smallest maximum link utilization).

From the subset of paths thus found, the path whose total length is minimum is then selected and all traffic originating at i and destined for j is routed over this path. The same procedure is applied to all nodes in each group.

It is important to note that the final capacity of each line is the least cost capacity (which corresponds to the average time delay) that can accommodate the total flow in that line.

The approach of the routing algorithms detailed in the following sections though consistent with these analysis for the selection of the primary paths, will proceed somewhat differently for the selection of the secondary, tertiary and fourth alternative paths.

The procedure for determining the feasible paths between all node pairs within a network is undertaken by implementing two algorithms. The first, which determines all the feasible paths as per section 4.2 except that all feasible paths are arranged in ascending order of weighted length and have certain constraints as mentioned in section 4.3. This in effect takes into consideration the physical length of the path as well as a weighted length in kilometres to represent any intermediate and additional XPRO traversed by a data packet between its source and destination node. The second selects from all the feasible paths found the best set of alternative paths between all node pairs. The best set of alternative paths between node pairs is determined by the "lowest weighted" length paths and those paths with the next lowest weighted path lengths that have an alternate "primary hop" to any of the previous best alternative paths found between the same node pair. This was a constraint stipulated by SAPONET. The manner in which these algorithms are implemented is purely dependent on the user's requirements and as explained in their respective sections, they may not necessarily have to be implemented at all in some user's applications.

In the following sections the above algorithms are presented with the definition of terms used in the algorithms given in APPENDIX E.

4.3 FEASIBLE PATH ALGORITHM

Given a set of N nodes, numbered arbitrarily from 1 to N and the $N \times N$ link matrix LM , whose elements LM_{ij} represent the physical length (trunk distance in kilometers) of the link connecting node i to node j (and node j to node i) over which traffic flows and various other weighing factors to be considered such as intermediate nodes, other additional processors, etc., it is possible to determine the shortest,

second shortest, third shortest etc. paths between all pairs of nodes in the network. Several different formulations of the shortest path algorithm and solutions of the problem can be found in the literature (3), (27), (28). This then is the first phase of the overall problem formulated in section 3.2 where:

Given : The number of nodes in the network N , where N is less than or equal to 35

The weight in kilometres per intermediate node in a path (NODEWT)

The weight in kilometres per additional XPRO in a path (XPROWT). (An XPRO is basically a packet processor unit)

The maximum acceptable number of hops (links) in a path (MH), where MH is less than or equal to 6

The maximum acceptable weighted-path length in kilometres (MAXLTH).

The node configuration matrix (see FIGURE 4(b)) in the following form: transit node, source node, destination node, number of additional XPROs that a data packet must go through in order to go from the source node to the destination node via the transit node.

The link matrix, that is, the physical length in kilometres of all the links in the form : node at one end of the link, node at the other end of the link and the physical length in kilometres of the link connecting the two nodes.

Find : All the feasible paths between all node pairs within the network and for each source-to-destination node pair, arrange their respective feasible paths in ascending order of weighted length.

In the context of this study and as mentioned in the introduction, a feasible path is defined as a path between a source and destination node where the number of nodes in the path is dependent on or less or equal to the maximum number of hops (MH) input by the routing manager. Additionally, if the path has more than three hops (a parameter stipulated for the SAPONET network due to the large physical distances between nodes) then its weighted path length must be less than the maximum acceptable weighted path length (MAXLTH) input by the routing manager. The constraints for a feasible path are therefore as follows:

- (i) number of nodes less or equal to MH in the feasible path
- (ii) for number of hops greater than three and number of nodes less than or equal to MH and if the path length is less or equal to MAXLTH then the path belongs to the set of feasible paths.

The weight in kilometres per intermediate node in a feasible path is a variable that is determined by the routing manager. For the SAPONET model a weighing factor of 500 km was used based on the average hop length within a feasible path. Additionally, the weighing factor was chosen with the assumption that any intermediate node encountered in a feasible path effectively adds an additional link to the path and therefore additional traffic flow results within the network. The weight in kilometres for each additional XPRO that a data packet

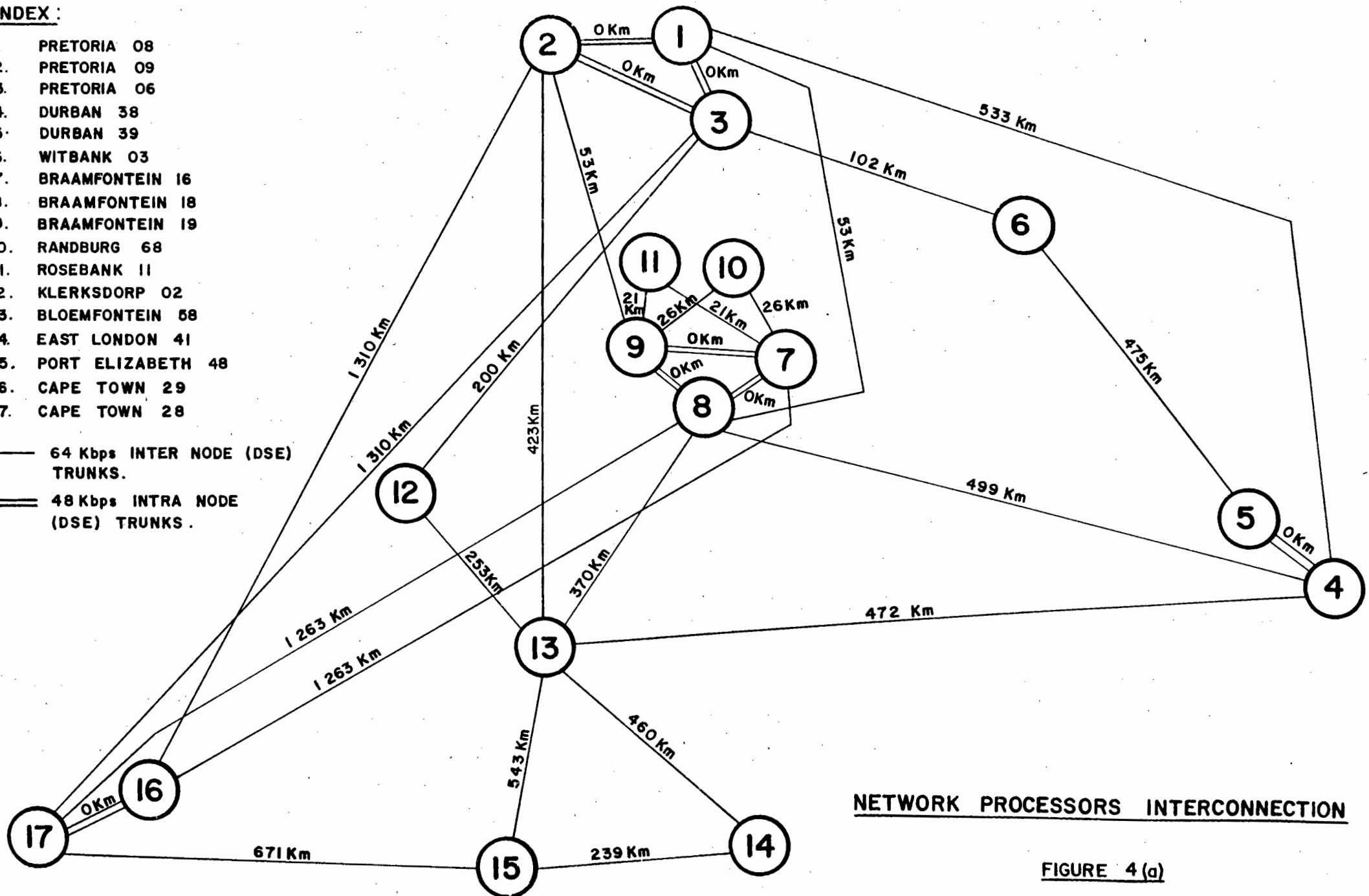
traverses on its path through an intermediate node is also a variable that is determined by the routing manager. For the SAPONET model a weighing factor of 5 km was used based as a percentage of the weighing factor used for the intermediate node. Using these figures it is possible to determine the weighted and physical length of each feasible path. The weighted path length contains the physical length of the path as well as the weighted lengths of each intermediate node and any additional XPRO traversed by the data packet. The maximum acceptable weighted path length in kilometres is determined by the routing manager and for the SAPONET model a limit of 5 000 km was chosen. In effect the maximum acceptable weighted path length limits the physical length of the path since it is also dependent on the number of hops in the path. This limitation is basically enforced to control the propagation delays that can be expected over long physical lines.

The node configuration matrix deals with those intermediate nodes (DSEs) that have multiple XPROs. FIGURE 4(b) to 4(d) illustrates the arrangements of XPROs at a few of the nodes for the network given in FIGURE 4(a). The local as well as inter-nodal inter-XPRO trunks are indicated with relation to the XPRO they are connected to, as well as the position within the XPRO. The local inter-XPRO trunks operate at 48 kbit/s and the inter-nodal inter-XPRO trunks operate at 64 kbit/s as shown in FIGURE 4(a). The throughput capacity of each XPRO is also indicated in FIGURE 4(b), 4(c) and 4(d). This can be either 0,3 Mbit/s or 0,5 Mbit/s. As mentioned in Chapter 2, the processing capacity of the switching node is assumed to be infinite and therefore the throughput capacity of each XPRO is not considered when establishing the feasible paths. However, if there are two possible feasible paths between a source and destination node and both paths have one intermediate node,

INDEX :

1. PRETORIA 08
2. PRETORIA 09
3. PRETORIA 06
4. DURBAN 38
5. DURBAN 39
6. WITBANK 03
7. BRAAMFONTEIN 16
8. BRAAMFONTEIN 18
9. BRAAMFONTEIN 19
10. RANDBURG 68
11. ROSEBANK 11
12. KLERKSDORP 02
13. BLOEMFONTEIN 58
14. EAST LONDON 41
15. PORT ELIZABETH 48
16. CAPE TOWN 29
17. CAPE TOWN 28

— 64 Kbps INTER NODE (DSE) TRUNKS.
 == 48 Kbps INTRA NODE (DSE) TRUNKS.

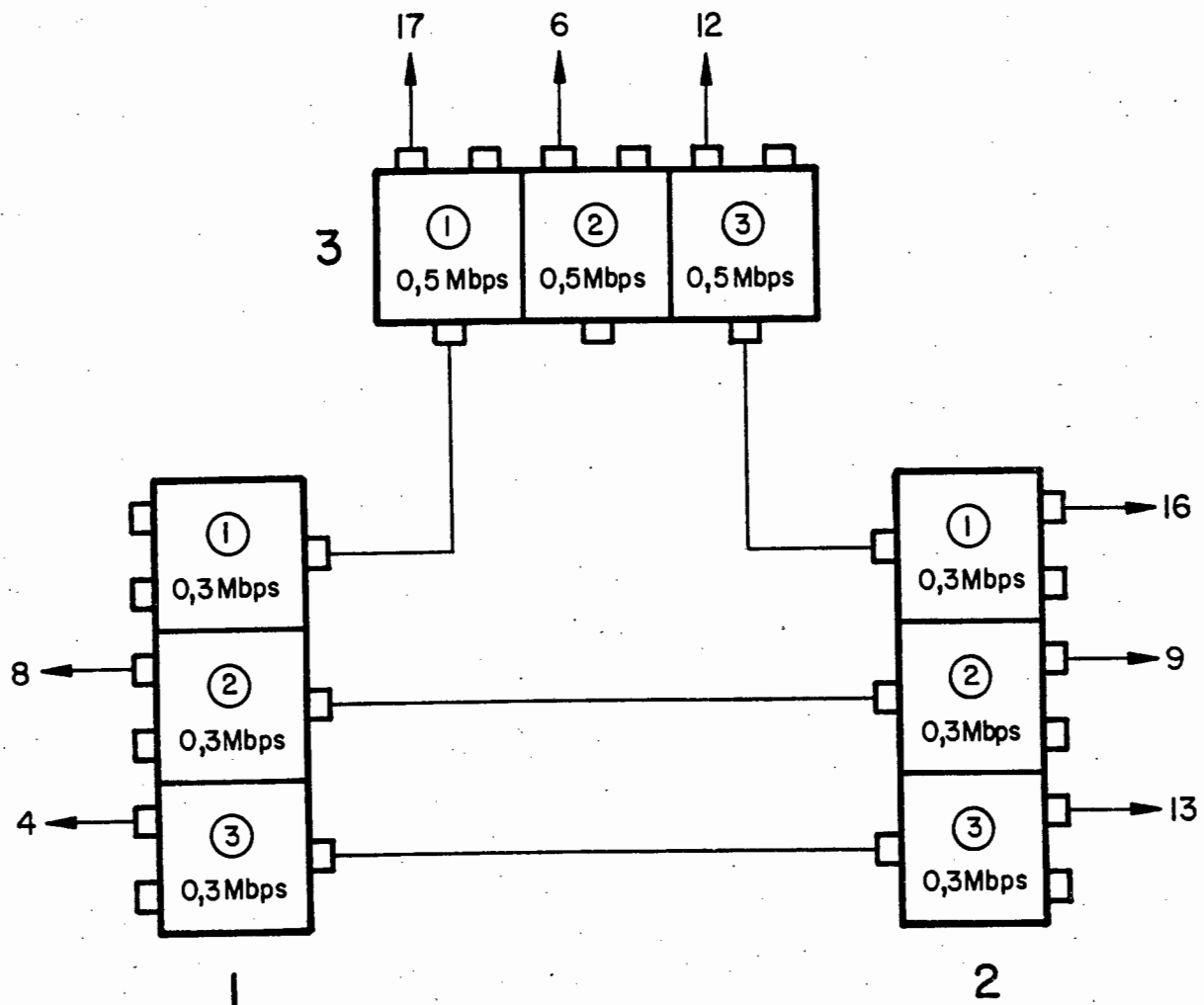


NETWORK PROCESSORS INTERCONNECTION

FIGURE 4 (a)

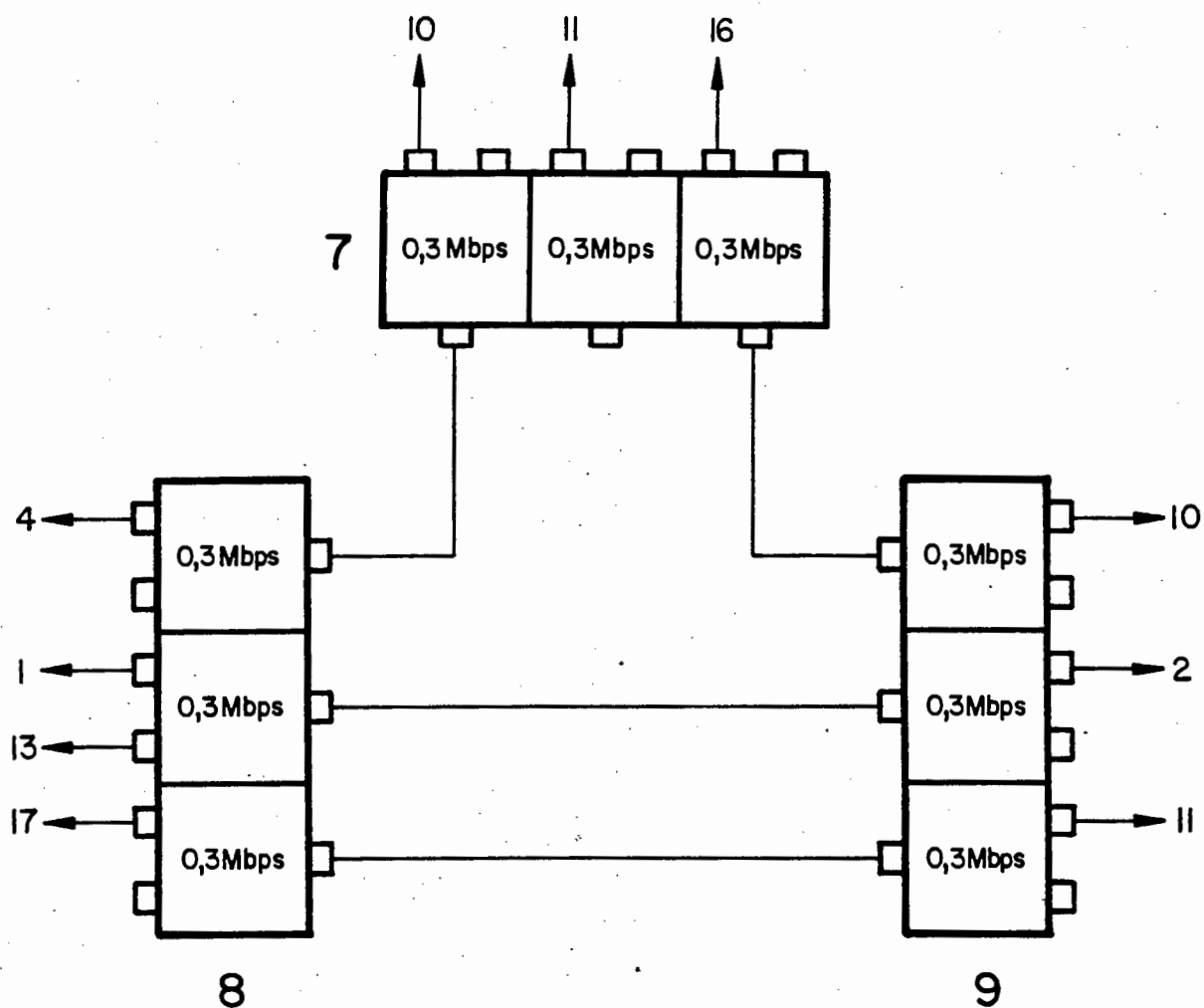
EXAMPLE OF A PORTION OF THE NODE CONFIGURATION MATRIX
AT NODE 3:

TRANSIT NODE,	SOURCE NODE,	DESTINATION NODE,	Nº OF ADDITIONAL XPRO'S
3	17	6	1
3	17	12	2
3	17	2	2
3	12	1	2
3	6	12	1
3	6	2	1
3	6	1	1
3	1	2	2



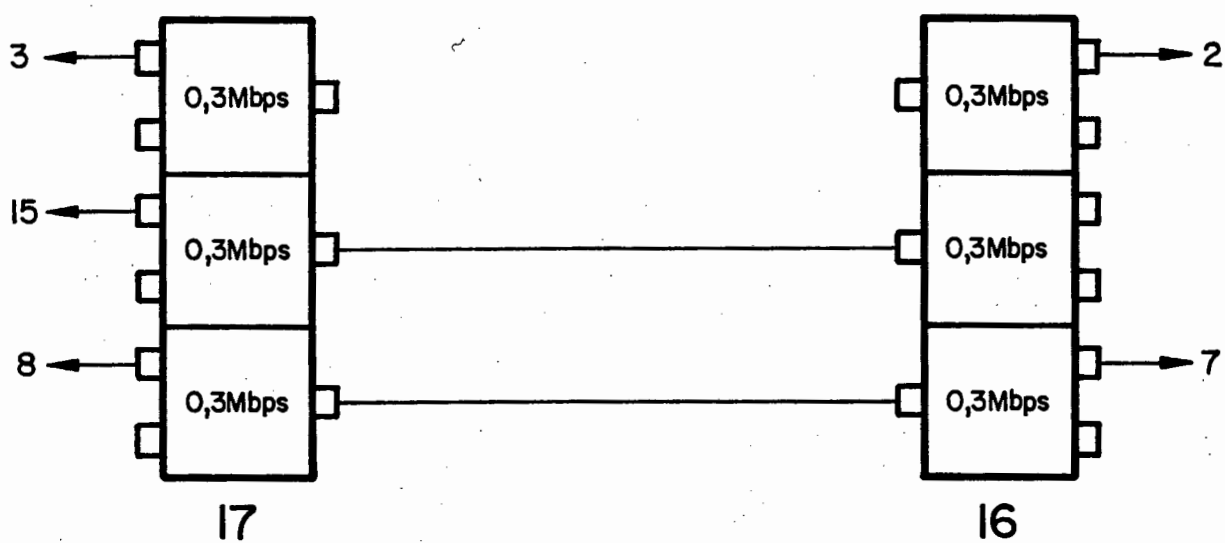
ARRANGEMENT OF XPROS AT NODES (DSE's) 1, 2 & 3

FIGURE 4 (b)



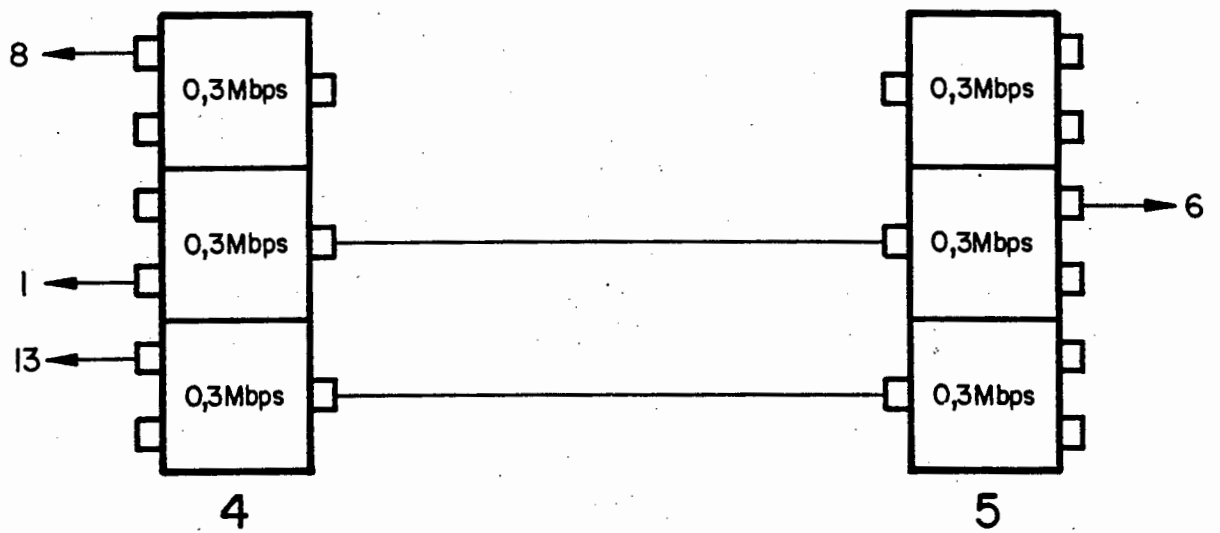
ARRANGEMENT OF XPROS AT NODES 7,8 & 9

FIGURE 4 (c)



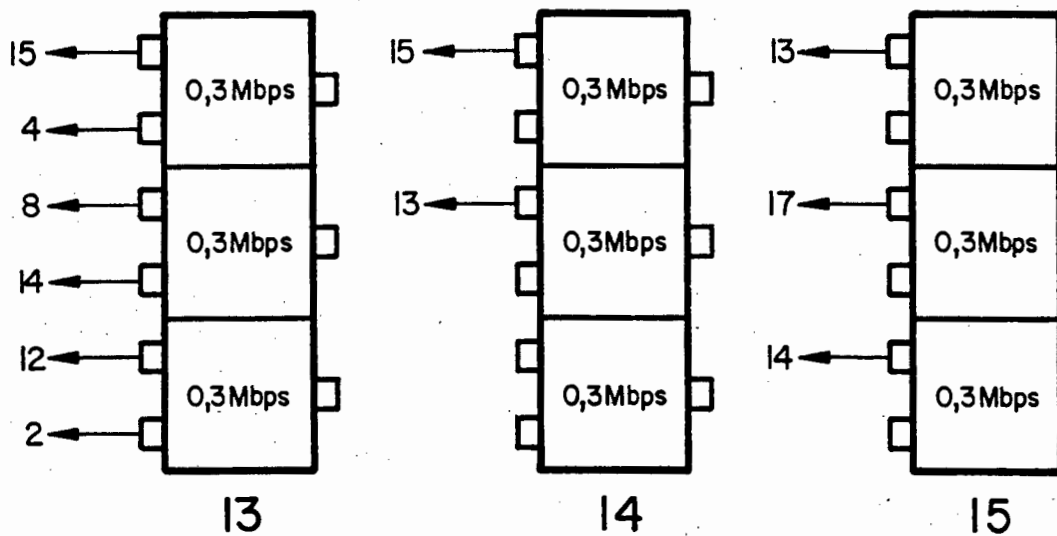
ARRANGEMENT OF XPROS AT NODES 16 & 17

FIGURE 4 (d)



ARRANGEMENT OF XPROS AT NODES 4 & 5

FIGURE 4 (e)



ARRANGEMENT OF XPROS AT NODES 13,14 & 15

FIGURE 4 (f)

<u>PATH</u>	<u>WEIGHTING PROCESS</u>	<u>WEIGHTED LENGTH OF PATH</u>	<u>PHYSICAL LENGTH OF PATH</u>
2-1-4		1033Km	533Km
1-8-7		558Km	53Km
9-2-13-8		1856Km	846Km
12-13-15		1306Km	796Km



≡ SOURCE NODE



≡ DESTINATION NODE



≡ INTERMEDIATE NODE (WEIGHTED 500Km FOR THIS EXAMPLE)



= INTERMEDIATE NODE PLUS AN ADDITIONAL XPRO (WEIGHTED 500Km AND 5Km RESPECTIVELY)



= INTERMEDIATE NODE PLUS TWO ADDITIONAL XPRO'S (WEIGHTED 500 Km, 5Km AND 5Km RESPECTIVELY)

NOTE: REFER TO FIGURES 4(b) TO 4(f) FOR THE ARRANGEMENT OF XPROS AT THE INTERMEDIATE NODES SHOWN IN THE EXAMPLES ABOVE.

EXAMPLES OF HOW PATHS ARE "WEIGHTED"

FIGURE 4 (g)

it is possible that at one intermediate node there are two XPROs and the other only one. In this example the latter feasible path could have the lowest weighted path length and it would therefore be chosen as the first choice path. Since the weighted path length is also dependent on the physical length of the path, it could be possible that both these feasible paths have identical weighted lengths. In this case the heuristic routing algorithm would be run to determine the first choice path based then on traffic flows already assigned to the network.

The link matrix is self explanatory and for the network shown in FIGURE 4(a) the physical distances between all nodes within the network is given. From this the 2-dimensional NXN link matrix can be established.

One of the networks on which this and all the other algorithms were simulated is shown in FIGURE 4(a). The arrangements of the XPROs at some of the nodes (DSEs) in the network are shown in FIGURE 4(b) to 4(f). Those nodes not shown do not have any additional XPROs. In FIGURE 4(b) an example of the 3-dimensional NXNXN node configuration matrix for one of the nodes in the network is given. FIGURE 4(g) shows examples of how the network components for different paths are "weighted" with the resultant physical and "weighted" length of these paths.

A basic outline of the program used to determine all the feasible paths between all node pairs within a network is given in APPENDIX F.

4.4 BEST ALTERNATIVE PATH ALGORITHM

The best alternative path algorithm selects the lowest weighted alternative paths between all node pairs in the network from all the feasible paths. The algorithm is simple and is defined as follows:

Given: The node configuration matrix. The feasible paths between all node pairs in the network.

Find : The best lowest weighted length alternative paths between all node pairs.

The best alternative paths between any node pair is defined, as in the introduction, as the path with the lowest weighted length and those paths with the next lowest weighted length that have an alternate "primary hop" (the first hop in a path) to any of the previous best alternative paths found between the same node pair.

There are many other possible routing policies that could be implemented (5), (16), (22), (29), where for example each source node in a path maintains full control over the route taken by the data packet. In this case the selection of the best, second best etc. path for the data packet could be taken by looking at all possible paths, that is, all the feasible paths and not necessarily only the best alternative paths.

The algorithms discussed in this and section 4.3 correspond to points (1), (2), and (3) shown in the basic heuristic algorithm. The main difference being that in H. Frank and W. Chou approach, feasible paths are grouped in ascending order of the number of intermediate nodes contained between source and destination. In this study, feasible paths are firstly grouped in ascending order of "weighted length" and then a further constraint that the second choice path must have an alternate "primary hop" to that of the first choice path.

A basic outline of the program used to determine all the best alternative paths between all node pairs within a network is given in APPENDIX G. In the following section the modified heuristic routing algorithm is presented.

4.5 THE MODIFIED HEURISTIC ROUTING ALGORITHM

In the basic heuristic algorithm detailed in 4.2, paths are selected which have minimum "resistance" to additional flow i.e. either paths whose maximum flow are a minimum, paths with the largest minimum residual capacity, or paths with the smallest maximum link utilization. In this study, four particular path types are considered. Tabled results are obtained for each of these four path types at various traffic inputs and thereafter their respective minimum average time delay for a packet within the network calculated and compared. The four main path types are as follows:

- (1) Maximum bandwidth paths as per section 4.2 case (b). These are those paths whose minimum link residual capacities are a maximum.
- (2) Minimum estimated average time delay paths. These are those paths that when selected provide the minimum average time delay in the network for a packet.
- (3) The lowest utilized primary hop paths. These are those paths whose minimum link residual capacity on the primary hops are a maximum.
- (4) The shortest paths. These are those paths whose weighted path lengths are a minimum.

Path type (1), (2) and (3) are determined based on traffic flow within the network, however path type (4) is available to the user when the shortest paths or the paths with the lowest weighted lengths are selected and are independent of the traffic flow within the network.

The modified heuristic algorithm can therefore be written as follows:

For each node i ($i = 1, 2, \dots, N$) routes are determined as per section 4.3 and 4.4 and nodes are grouped as follows:

- (i) All nodes connected to node i by the best alternative paths (lowest weighted length paths).
- (ii) All nodes connected to node i by the next best alternative path (next lowest weighted length paths).
- ⋮
- (k-1) All nodes connected to node i by the next best alternative path [next lowest weighted length paths which is equal to $(MAXLTH-1)$].
- (k) All nodes connected to node i by the next best alternative path (lowest weighted length paths which is equal to $MAXLTH$, where $MAXLTH$ is defined by the routing manager).

Traffic is first routed from node i to any node j which is directly connected to i over link (i, j) and to any node j which is connected to i via the only lowest weighted path length between these two nodes. This effect defines some of the primary paths and consequently after this stage, some flows are assigned to the network. For any node j in a group, all best alternative paths between node i and j are examined and functions of the flow assigned to each link and the required capacity for the respective flow evaluated (in the case of primary path processing these would be the two or more paths with the same source to destination nodes and equal weighted path lengths).

If $\pi_1, \pi_2, \dots, \pi_m$ are all the best alternative paths $B\pi_{ij}$ from node i to node j then the evaluation functions $E_1, E_2, \dots, E_m$ (which correspond to whether path type

1, 2 or 3 is chosen) can be written as follows:

Let Π_x contain the links $(i_0, i_1), (i_1, i_2), \dots, (i_{k-1}, i_k)$ where $i_0 = i$ the source node and $i_k = j$ the destination node, (i_0, i_1) is the primary hop, (i_1, i_2) the secondary hop, etc. Functions $g_{i1}, g_{i2}, \dots, g_{ik}$ can now be defined such that for all h ($h \geq 1$) either:

(a) g_{ih} is equal to the difference between the least cost capacity (in this case the discrete capacity of the line) required to accommodate the flow in (i_{h-1}, i_h) and the value of that flow - g_{ih} is then said to be equal to the residual capacity of line (i_{h-1}, i_h) .

(b) g_{ih} is equal to the ratio of the flow in (i_{h-1}, i_h) and the least cost capacity that can accommodate the flow - in this study $h=1$ and g_{i1} is then said to be equal to the link utilization factor of the primary hop (i_0, i_1) .

A third case is investigated where all the best alternative paths between node i and node j are evaluated and the path which provides the minimum estimated average time delay for a packet in the network is chosen.

Dependent on the user's request either one of the following is processed:

(i) case (a) above where the residual capacity of the path
 $E_x = \min_{1 \leq h \leq k} (g_{ih})$ and then the subset of best alternative

paths Π_k are considered (or in the case of primary path selection the subset of two or more best alternative paths with equal weighted length Π_k are considered) such that the maximum residual bandwidth of the paths $E_{ki} = \max_{1 \leq x \leq k} (E_x)$

(these are type 1 paths).

(ii) previous case (b) where $E_x = g_{il}$ (only the primary link is considered) and the subset of best alternative paths π_k is considered (or in the case of primary path selection the subset of two or more best alternative paths with equal weighted length π_k are considered) such that $E_{k1} = \min E_x$ in other words this is the path in the set

$$1 \leq x \leq k$$

of feasible paths with the minimum utilization factor over the primary link (type 3 paths).

(iii) The third case where the subset of best alternative paths π_k are considered (or in the case of primary path selection the subset of two or more best alternative paths π_k with equal weighted lengths are considered) such that

$$T = \sum_{i=1}^P \lambda_i [T_i + P_{di} + NP_{di}] \text{ is a minimum, in other words}$$

this is the path in the set of best alternative paths which ensures a minimum estimated average time delay for a packet within the network (these are type 2 paths). A simple example of how the average packet time delay in the network is calculated is shown in APPENDIX I.

The following summarises the routing problem as:

Given : The number of nodes in the network N
where N is less than or equal to 35.

The number of links in the network P , where P is less than or equal to 70.

The path type, that is, 1 = maximum bandwidth paths

2 = minimum estimated average time delay paths

3 = the lowest utilized
primary hop paths

4 = the shortest paths -
those paths with the lowest weighted path lengths.

The maximum acceptable utilization factor on all
links under normal conditions (maximum of 100).

Whether the modified combination of paths are re-
quired (1=YES, 0=NO). The modified combination of
paths provides the user with primary and secondary
paths so that either one of the first three re-
quirements for the path type above is met and then
tertiary and fourth alternative paths such that
they are the respective shortest paths. This
requirement was included since the probability of
more than two links being down were small.

The node configuration matrix in the form as
detailed in section 4.3.

The link capacity matrix, that is, the capacity of
the link connecting two neighbouring nodes in the
form: node at one end of the link, node at the
other end of the link, capacity of the link
between the two nodes in bits per second.

The link matrix in the form as detailed in section
4.3.

The node classes, that is, the nodes of the
network grouped into classes of high, medium, or
low traffic-carrying nodes in the form of a three
by N dimensional array where the high traffic-
carrying nodes occupy the first row, the medium
traffic-carrying nodes the second row and the low
traffic-carrying nodes the third row of the array.

The estimated average to peak ratios of the node classes in the form: high traffic-carrying nodes peak ratio, medium traffic-carrying nodes peak ratio, low traffic carrying nodes peak ratio.

The traffic matrix, that is, the estimated average traffic flow between all node pairs within the network in the form: source node, destination node, estimated average traffic flow (λ_i) in bits per second. (Since it has been assumed that the packet length is fixed this data is given in b/s, however, in the main program the entries of the traffic matrix are converted back to packets per second.)

The best alternative paths between all node pairs in ascending order of weighted length from which the primary, secondary, tertiary and fourth alternative paths must be chosen in the form: weighted length of path followed by the path information from source node to destination node.

A data file containing all nodes in the network that have two or more links directly connected to it and indicating all possible combinations of two links down for each of these nodes in the form: node that has two or more links directly connected to it (the "working node" is defined here as a node in the network that has two or more other nodes connected directly to it), node at other end of one direct link, node at other end of a different direct link.

A data file containing all the possible combinations of three links down from each node in the network that has more than three links directly connected to it in the form: node that has three or more than three links directly connected to it (the "working node" is defined here as a node in

the network which has three or more other nodes connected directly to it), node at other end of one direct link, node at other end of different direct link to the first one, node at other end of a direct link different to either of the first two direct links.

Find : A fixed routing table for the network containing the primary (lowest weighted length paths) and secondary and where possible the tertiary and fourth alternative paths between all node pairs. The fixed routing table must be determined by ensuring that the lowest value of average time delay for a packet within the network is found.

In effect path type 2 conforms with the requirements as defined in section 3.2, however the other options were provided so as to compare the average time a packet would spend in the network if they were chosen by the user. These results are discussed later in Chapter 5.

The maximum acceptable utilization factor on all links under normal network conditions allows the user to be informed of any links exceeding limitations specified by the routing manager. A prompt will be given to the routing manager if the set limits are exceeded. For the SAPONET model a maximum utilization factor of 70 percent traffic occupancy on any link within the network is specified

The modified combination of paths provide the user with the option of choosing his two most important paths, the primary and secondary paths, so that either one of path type one to three are met and thereafter the tertiary and fourth alternative paths are chosen so that they are the shortest paths.

The information pertaining to the node classes is included in the input data to allow for the grouping of the high, medium and low traffic-carrying node. In the SAPONET model, this information was significant since a small portion of the total number of nodes carried the majority of the traffic loading within the network. The average to peak ratios of different node classes allows the routing manager to estimate peak traffic conditions and therefore select his optimum routes under these conditions rather than when the traffic is lightly loaded. When this study was undertaken figures obtained for the total traffic generated and received by nodes within the SAPONET packet switched network were rather low. The estimated average-to-peak ratios of the node classes provided a useful means of increasing traffic flows within the network and thereafter observing the effect on the average time a packet spent in the network for the different possible combinations of paths.

A basic outline of the modified heuristic routing algorithm is given in APPENDIX H.

CHAPTER 5
-----DISCUSSION OF RESULTS
-----5.1 INTRODUCTION

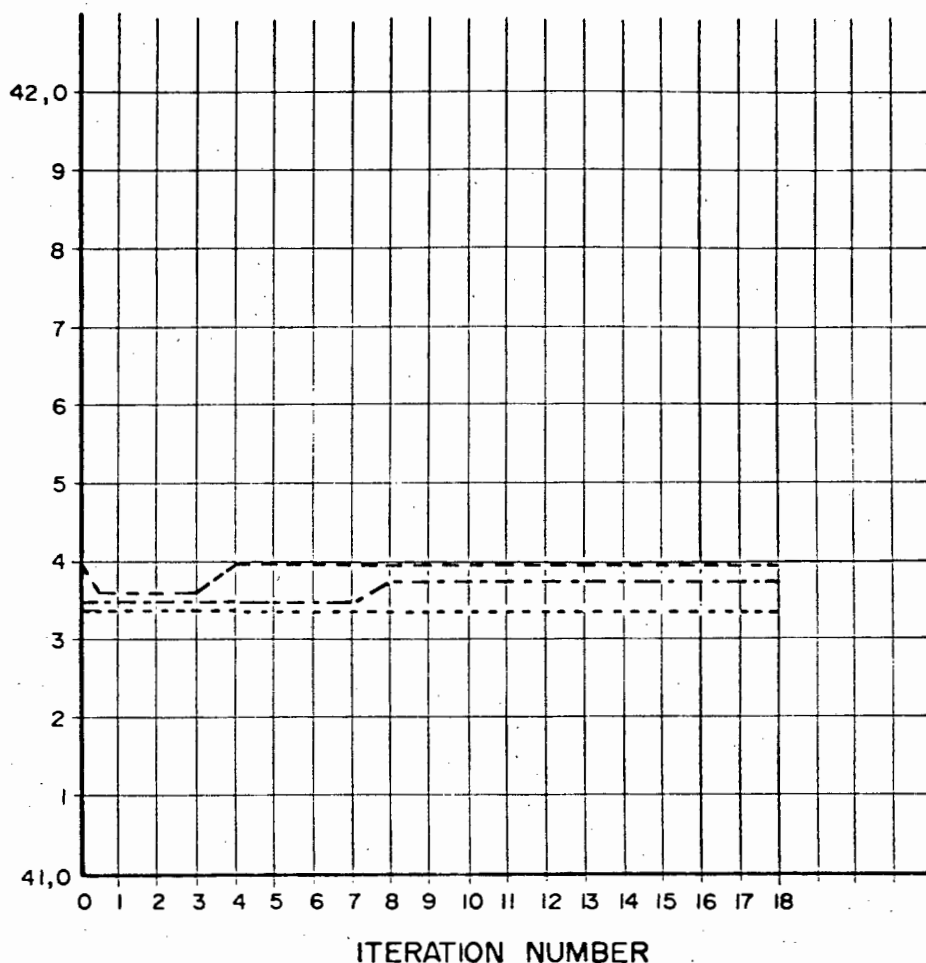
In order to demonstrate the effectiveness of the modified heuristic routing algorithm detailed in Chapter 4, each phase, that is, the primary path, the secondary path, the tertiary path and the fourth alternative path algorithms, was tested by four separate test programs and a summary of the results obtained is given for one of the many example networks on which this routing method has been applied. The network configuration, (see FIGURE 4(a) to 4(f)) examined corresponded to the initial proposals for the new SAPONET packet-switched network.

All software was written in FORTRAN and run on the SPERRY UNIVAC main computer. A copy of the listings and results of all the tables generated by the programs were forwarded to SAPONET in Pretoria for further analysis.

In addition to computing the minimum time delay for each traffic matrix, the following combination of paths found by the programs in generating this time delay, were recorded and compared:

- (i) The maximum bandwidth paths
- (ii) The minimum estimated time delay paths
- (iii) The lowest utilized primary hop paths
- (iv) The lowest weighted length paths, that is, the shortest paths

TOTAL AVERAGE
WEIGHTED TIME
DELAY FOR THE
PACKET IN ms



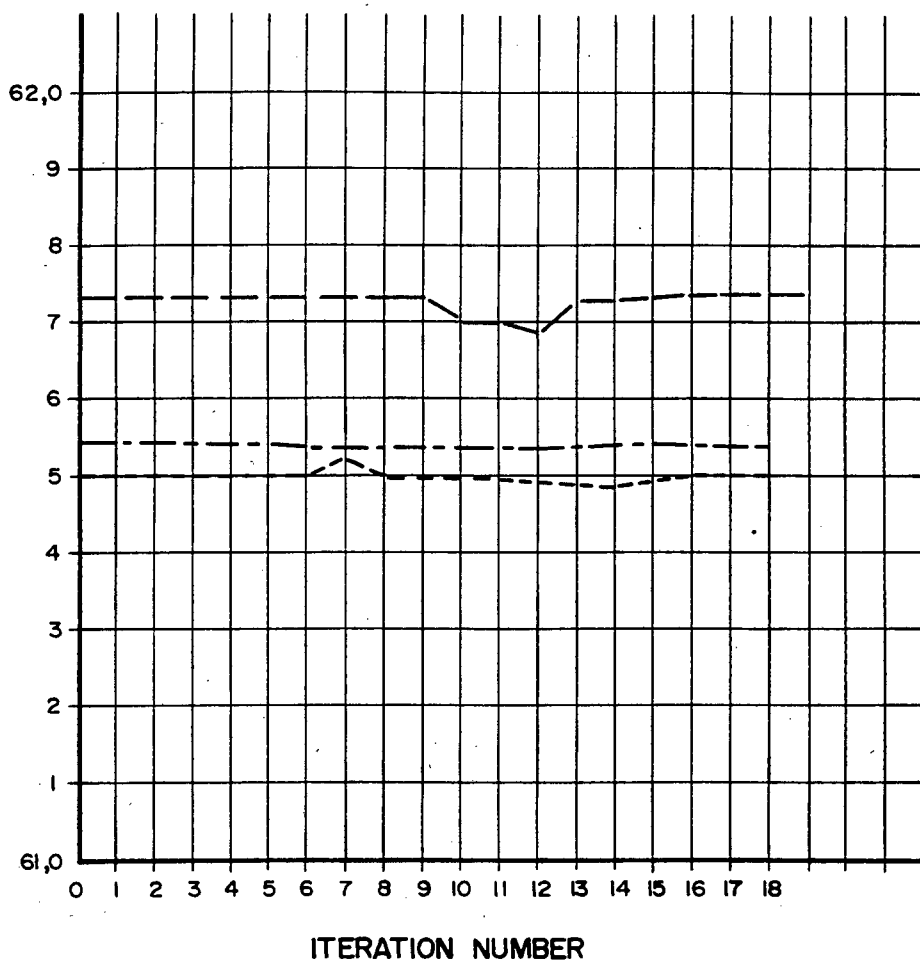
- Maximum bandwidth paths
- Minimum estimated time delay paths
- . - . - Paths with the lowest utilized primary hops

NOTE: EACH ITERATION INDICATES THAT A CERTAIN COMBINATION OF PATHS HAVE BEEN SELECTED WHICH IN TURN PRODUCE THE TIME DELAY SHOWN.

TOTAL AVERAGE WEIGHTED TIME DELAY FOR THE PACKET IN ms
WITH A TOTAL TRAFFIC INPUT OF 172 Kbps VERSUS THE ITERATION
NUMBER CARRIED OUT

FIGURE 5(a)

TOTAL AVERAGE
WEIGHTED TIME
DELAY FOR THE
PACKET IN ms



- Maximum bandwidth paths
- Minimum estimated time delay paths
- Paths with the lowest utilized primary hops

TOTAL AVERAGE WEIGHTED TIME DELAY FOR THE
PACKET IN ms FOR A TOTAL TRAFFIC INPUT OF 412 kbps
VERSUS THE ITERATION NUMBER CARRIED OUT.

FIGURE 5 (b).

In the case of the selection of the primary paths the comparison included results of paths selected by a non-bifurcated flow-deviation method (36). APPENDIX D gives details of the flow deviation and non-bifurcated flow deviation algorithms.

5.2 PRIMARY PATH SELECTION

FIGURES 5(a) and 5 (b) show the total weighted minimum estimated time delay for a packet (this is T derived in Chapter 2 with the propagation and nodal processing delays fixed) once all primary paths have been selected for all possible source to destination node pair combinations with traffic inputs of 172 kbit/s and 424 kbit/s respectively and for path combinations (i), (ii) and (iii) versus the iteration number carried out. The network traffic input mentioned here and in all future results is the total amount of traffic in kbit/s input into the communication network and is obtained from the traffic matrix $R=r_{ij}$ where the total traffic input is:

$$\text{Traffic input} = \sum_{\substack{i=1 \\ j=1 \\ i \neq j}}^N r_{ij}$$

Where: N is the number of nodes in the network.

From these results the following observations can be made:

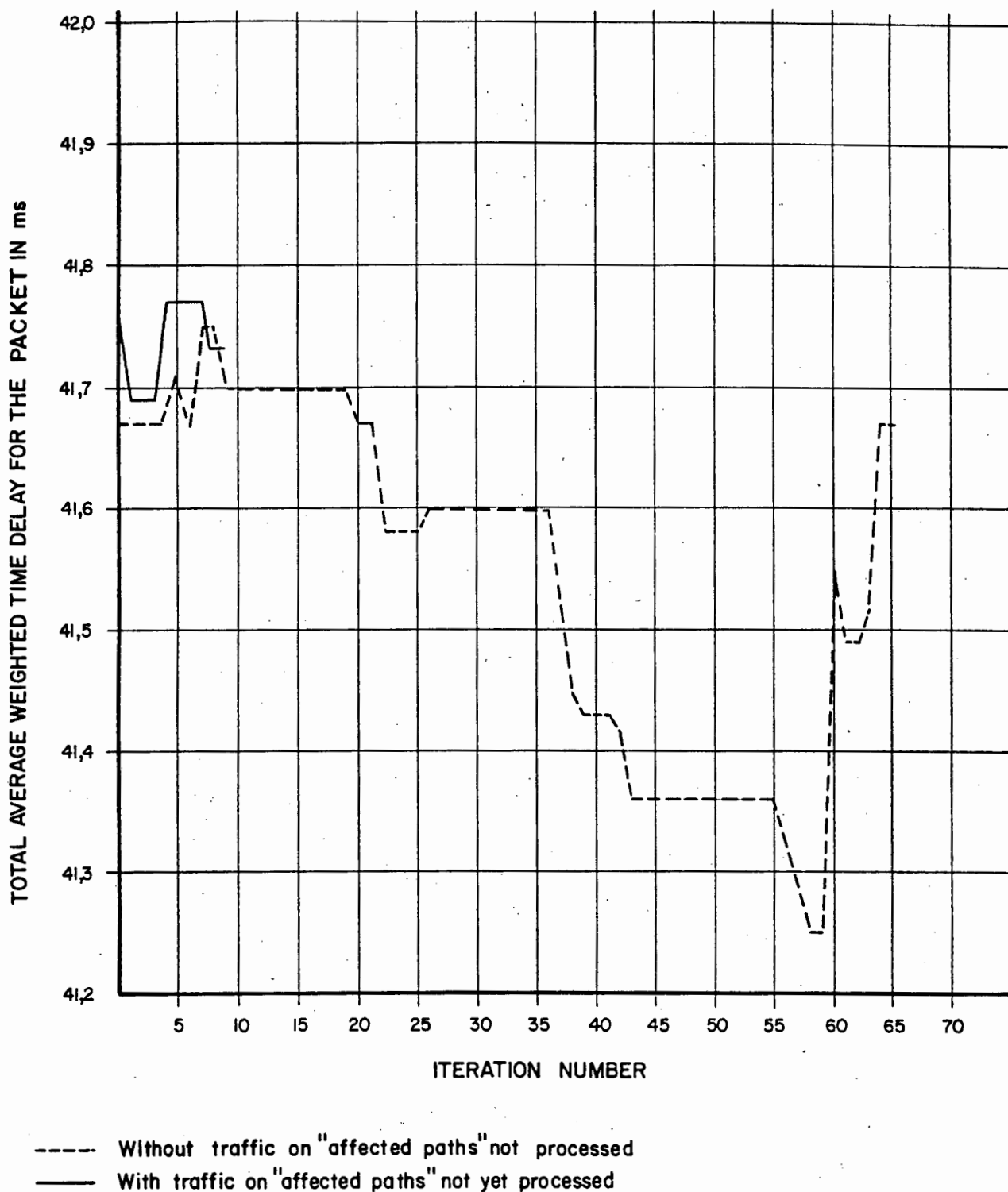
- (a) That for the particular configuration of the network given in FIGURES 4(a) to 4(f), there are 18 different source to destination node pairs, where for each node pair there are two or more paths with the identical

number of intermediate nodes and the same weighted path length. These are the affected paths mentioned in section H.1.1.

- (b) After each iteration a different or the same combination of the best paths for the 18 source-to-destination nodes is chosen from the affected paths and these paths are then added to those fixed primary paths (see section H.1.1) already chosen and the total time delay checked with the previous results. Results indicate that a better "optimal" solution for the best combination of affected paths can be obtained for both traffic inputs if the iterations are carried out.
- (c) The lowest value, for both traffic inputs, for the time delay T is obtained when selecting the best combination of paths from the affected paths, such that they are the paths with the minimum estimated time delay.

With reference to the algorithms detailed in section H.1.1 and section H.1.5 it is clear that when the first affected source to destination node pair paths are being processed, then there is no traffic flowing on the other affected source to destination node pairs as they have not been assigned, that is, a decision is being made on which best path should be taken when all the other paths are not fixed. This in effect does not produce an accurate approximation of the flows that can be expected on each link in the network. A routine was therefore added to the test program, which assigned one of the affected paths for each source to a destination node not yet processed as the path that would be chosen. Traffic was routed along these paths as well.

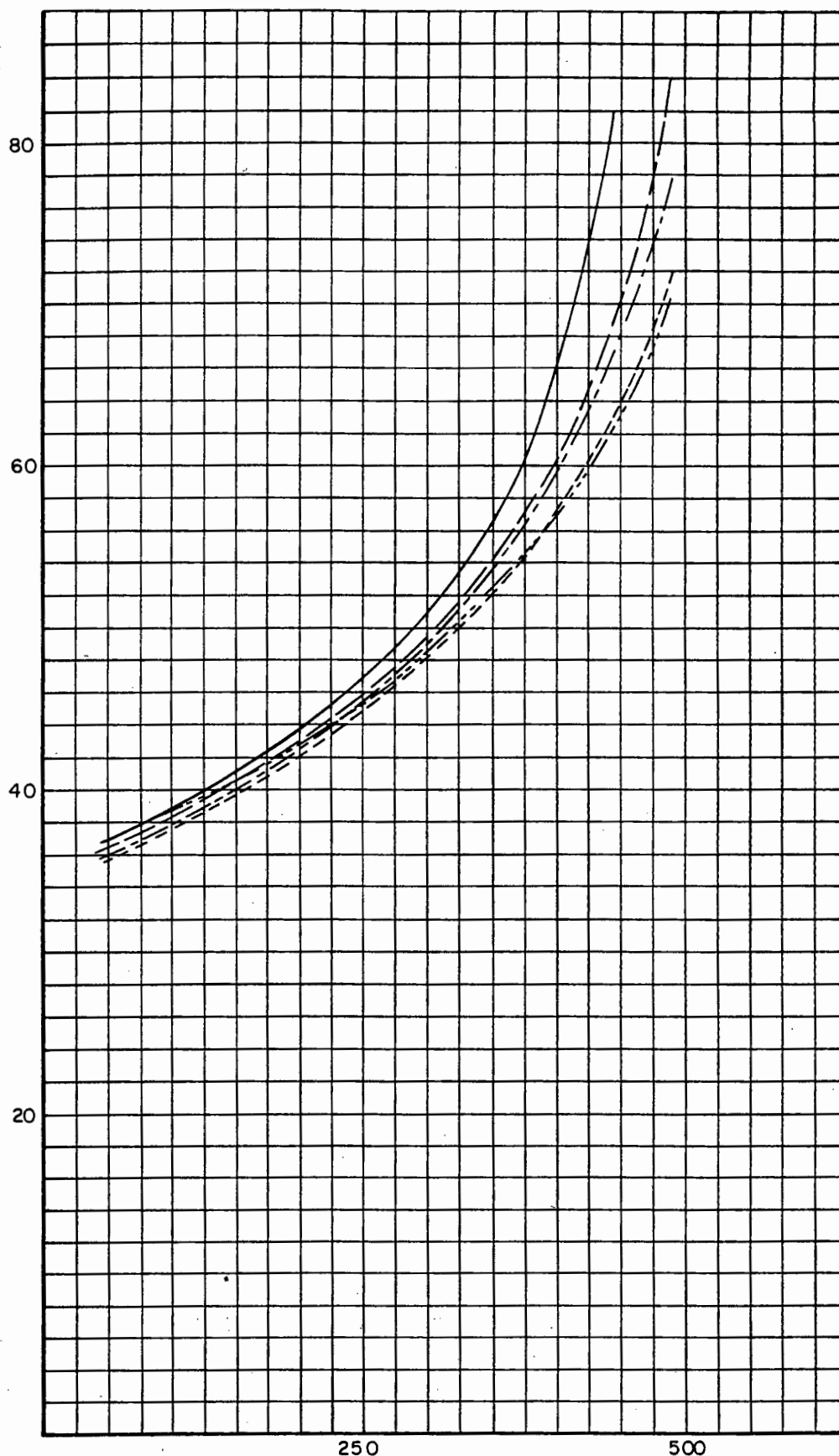
FIGURE 6(a) shows the minimum estimated time delay T for a traffic input of 380 Kbit/s versus the iteration number for the case when the decision-making is carried out without



COMPARISON FOR A DIFFERENT NETWORK TO THAT SHOWN IN FIGURE 4(a) OF TIME DELAY FOR THE PACKET OBTAINED FOR THE MINIMUM ESTIMATED TIME DELAY PATHS VERSUS ITERATION CARRIED OUT WHEN TRAFFIC IS NOT GENERATED ON THOSE "AFFECTED PATHS" NOT PROCESSED AND WHEN TRAFFIC IS GENERATED ON THOSE "AFFECTED PATHS" NOT YET PROCESSED.

FIGURE 6(b)

TOTAL WEIGHTED
AVERAGE TIME
DELAY FOR THE
PACKET IN ms



- Maximum bandwidth paths
- .-.-.- Minimum estimated time delay paths
- Shortest path
- Paths with lowest utilized primary hops
- Paths chosen from non-bifurcated flow deviation algorithm

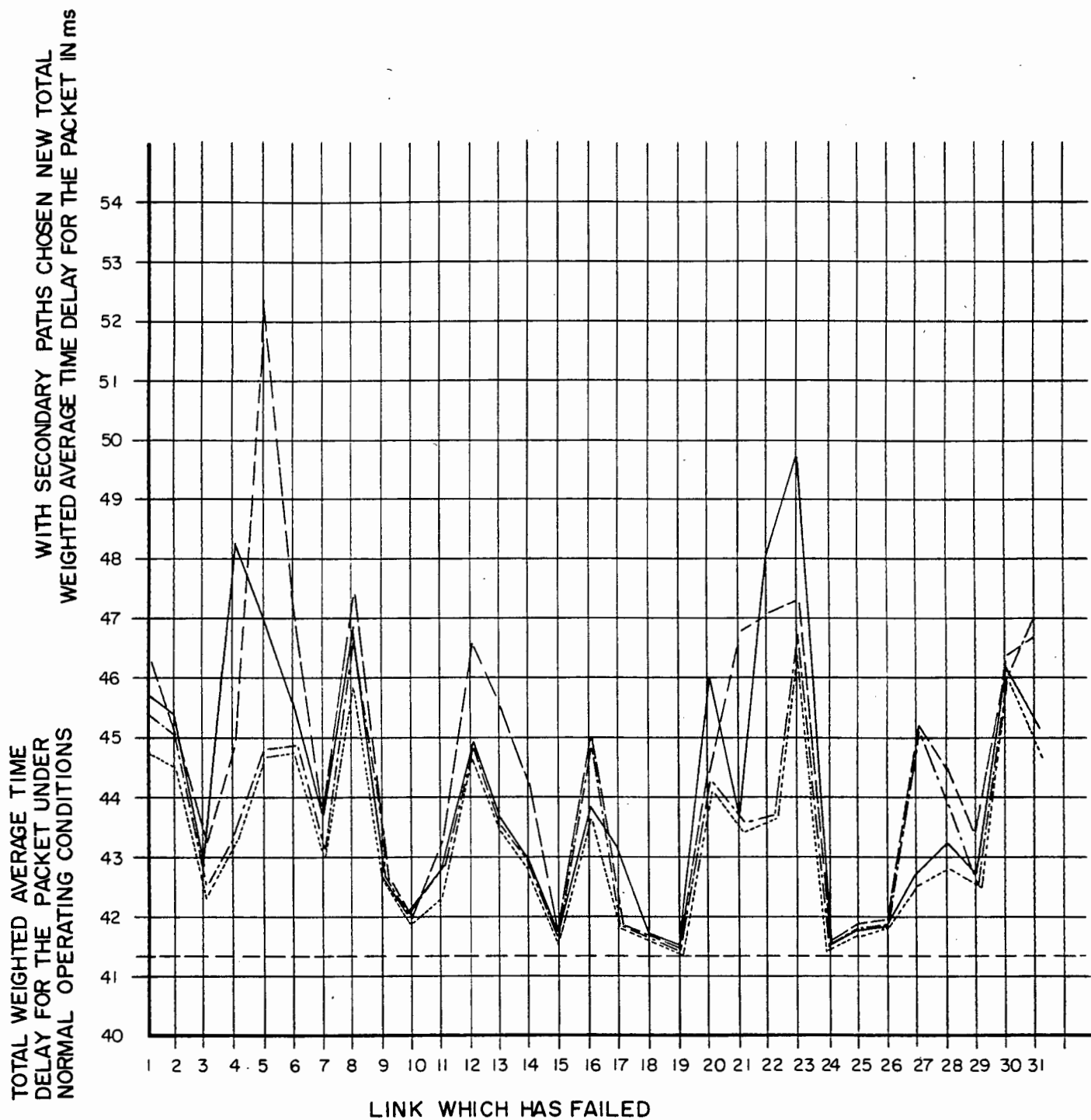
COMPARISONS OF THE DIFFERENT COMBINATIONS OF PATHS OBTAINED
WITH VALUES OF TIME DELAY VERSUS VARIOUS INPUT TRAFFIC LEVELS

FIGURE 7

traffic generated on those paths not processed and when the decision-making is carried out when traffic is generated by a path chosen from those paths that have not yet been processed, so that there is traffic on all paths except the path being processed.

From these results it can be seen that there is no clear advantage gained by including the routine which ensures a better approximation of the flows on each link in the primary path algorithm. It is important to note that the results obtained for the particular example network are not necessarily true for all networks. In FIGURE 6(b) a different example network produced results where there were more than 60 different source-to-destination node pairs with two or more paths with an identical number of intermediate nodes and the same weighted path length. Due to the large increase in CPU time only a few iterations were carried out on this network. However, results obtained were similar to those shown in FIGURE 6(a), in that there was no clear advantage obtained by implementing the additional routine and therefore this routine was excluded from the primary, as well as the secondary, tertiary and fourth alternative path algorithms.

FIGURE 7 shows the minimum estimated time delay T after iterations were carried out versus various traffic inputs for path combinations (i) to (iv) as well as the results obtained for the minimum estimated time delay T when the non-bifurcated flow deviation algorithm was run at various traffic inputs. Considering combination (i) to (iv), it is clear that the combination of paths with the minimum estimated time delay provides the user with the best "optimum" solution for all traffic levels, especially at the higher traffic inputs. For the higher traffic inputs, however, the selection of primary paths obtained from the non-bifurcated flow deviation algorithm were definitely superior.

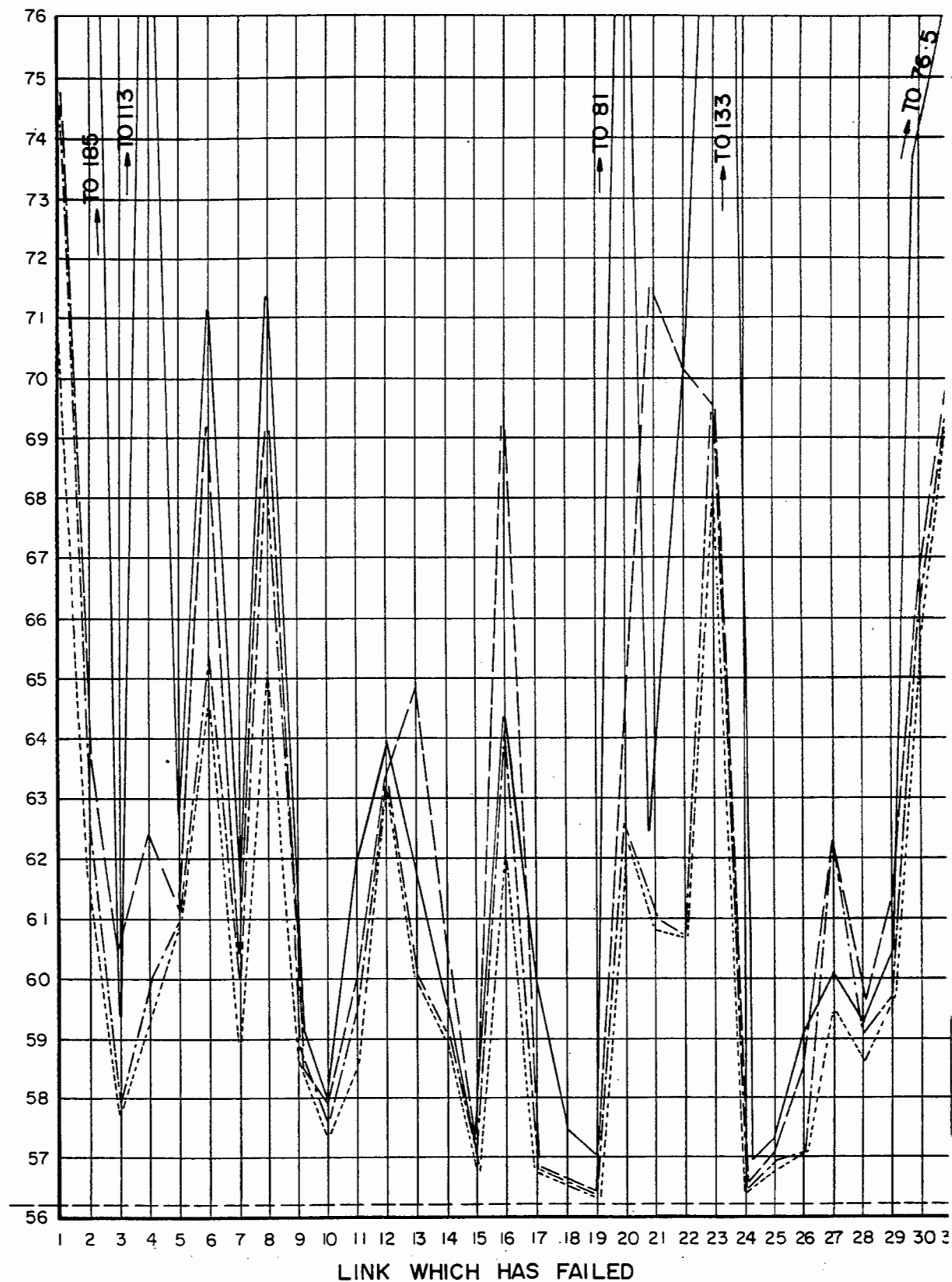


NEW TOTAL WEIGHTED AVERAGE TIME DELAY WITH A TRAFFIC INPUT OF 172Kbps UNDER LINK FAILURE CONDITIONS AND WITH SECONDARY PATHS CHOSEN FOR ALL FOUR COMBINATIONS VERSUS THE LINK WHICH HAS FAILED

FIGURE 8 (a)

WITH SECONDARY PATHS CHOSEN NEW
TOTAL WEIGHTED AVERAGE TIME DELAY
FOR THE PACKET IN ms.

TOTAL WEIGHTED AVERAGE
TIME DELAY FOR THE PACKET
UNDER NORMAL OPERATING
CONDITIONS.



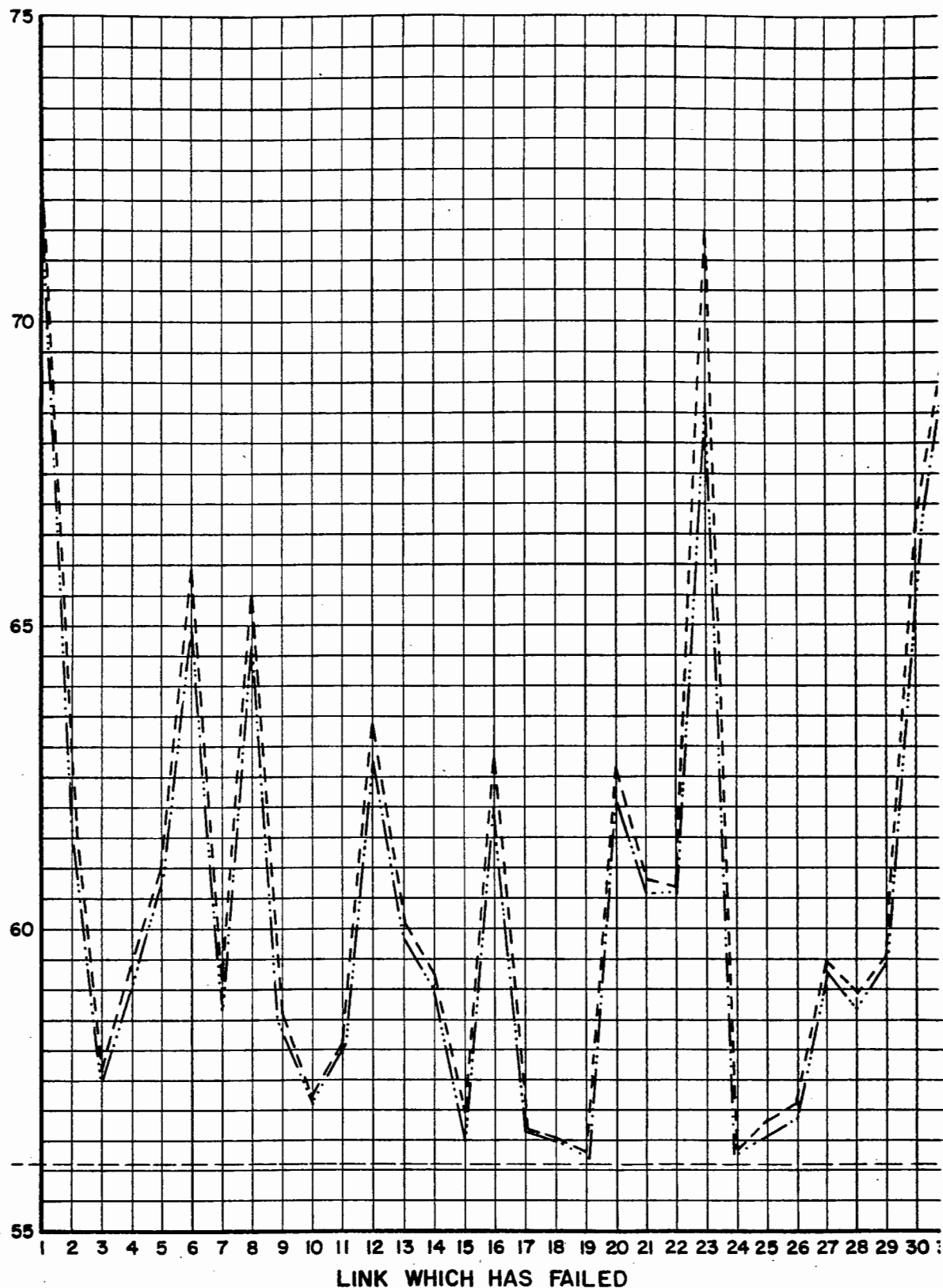
- · — Maximum bandwidth paths
- - - Minimum estimated time delay paths
- - - Paths with the lowest utilized primary hops
- Shortest paths

NEW TOTAL WEIGHTED AVERAGE TIME DELAY WITH A TRAFFIC INPUT OF 380Kbps UNDER LINK FAILURE CONDITIONS AND WITH SECONDARY PATHS CHOSEN FOR ALL FOUR COMBINATIONS VERSUS THE LINK WHICH HAS FAILED

FIGURE 8 (b)

WITH SECONDARY PATHS CHOSEN NEW
TOTAL WEIGHTED AVERAGE TIME DELAY
FOR THE PACKET IN ms.

TIME DELAY UNDER
NORMAL OPERATING
CONDITIONS.



--- Without iterations
— With iterations

COMPARISON OF NEW TOTAL WEIGHTED AVERAGE TIME DELAY OBTAINED WITH
AND WITHOUT ITERATIONS CARRIED OUT SO AS TO OBTAIN A MORE "OPTIMUM
COMBINATION OF SECONDARY PATHS VERSUS THE LINK WHICH HAS FAILED

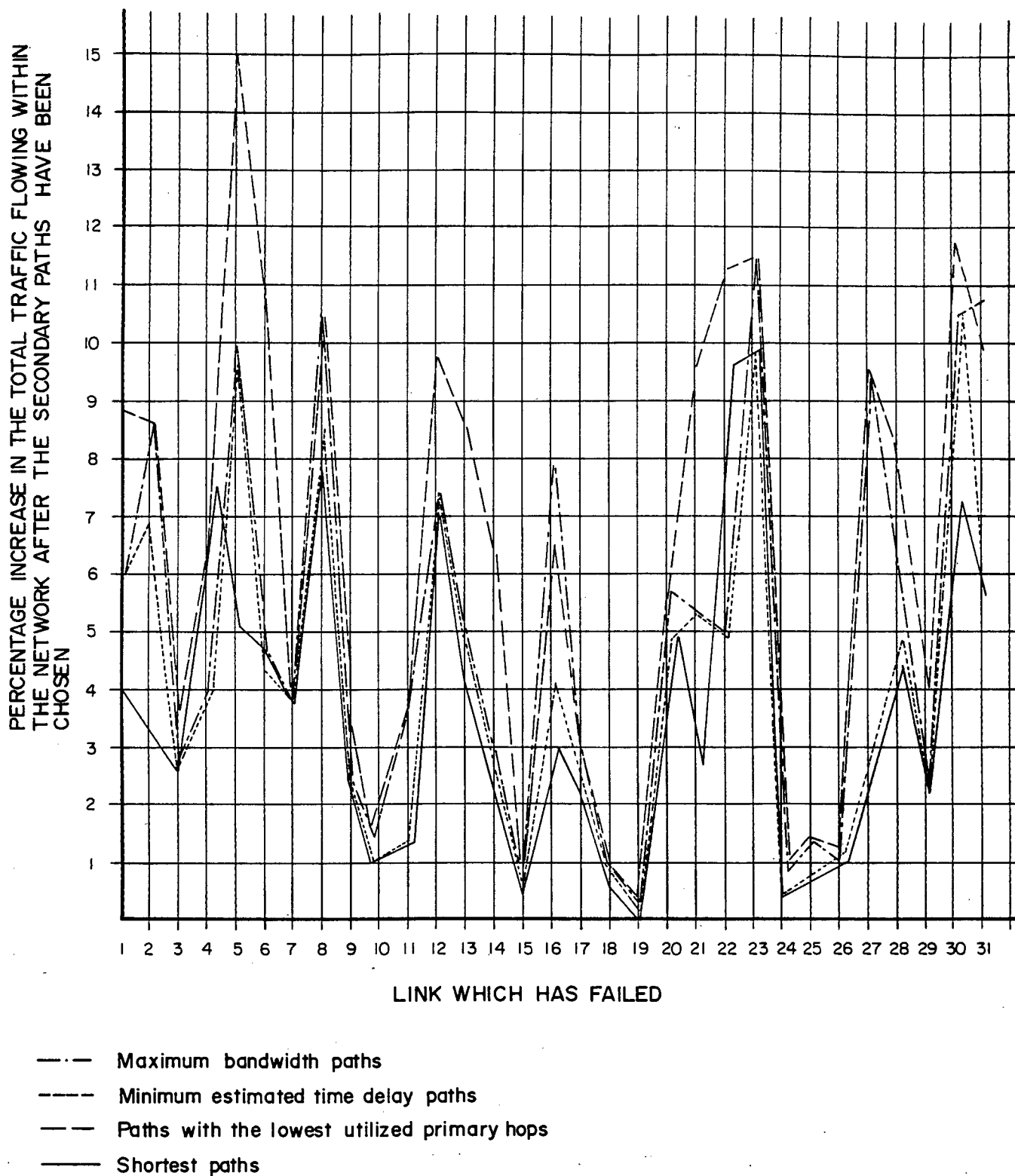
FIGURE 9

5.3 SECONDARY PATH SELECTION

FIGURE 8(a) shows the new total weighted minimum estimated time delay T obtained for a packet with a traffic input of 172 Kbit/s when the best combination of secondary paths have been chosen after iterations, so that they satisfy either path combination (i), (ii), (iii) or (iv) versus the link which has failed.

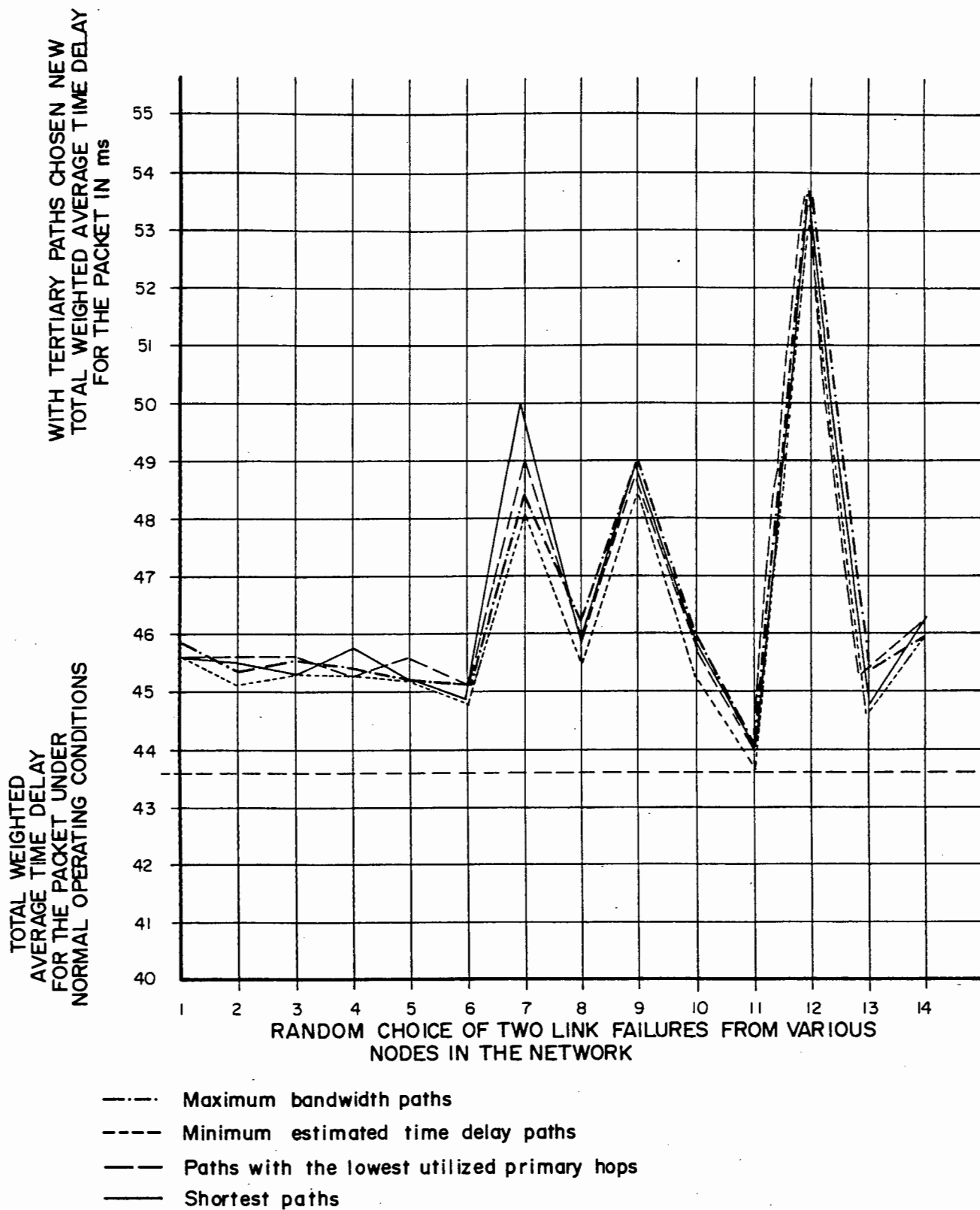
It is clear from these results that, for each link failure, the combination of paths which have the minimum estimated time delay provides the user with the "optimum" selection of alternative paths. FIGURE 8(b) shows the results obtained for a higher traffic input of 380 Kbit/s where, in most cases of link failures, the comparison of the four possible path combinations indicates that the combination of paths chosen with the minimum estimated time delay are even more significantly superior to those obtained when comparing the paths at the lower traffic input. Other valuable information obtained from these graphs is that peaks do occur in the values obtained for the minimum estimated time delay of a packet under certain link-failure conditions. These links in turn can be given a higher priority so as to ensure that they do not regularly fail.

FIGURE 9 shows the new total weighted minimum estimated time delay T with a traffic input of 380 Kbit/s when iterations are carried out and when iterations are not carried out and then the combination of secondary paths are chosen so that they satisfy (ii) versus the link that has failed. The results show that in most cases, for the tested network it was for 80% of the link failures, a more "optimum" combination of alternative (secondary) paths can be found by performing iterations.



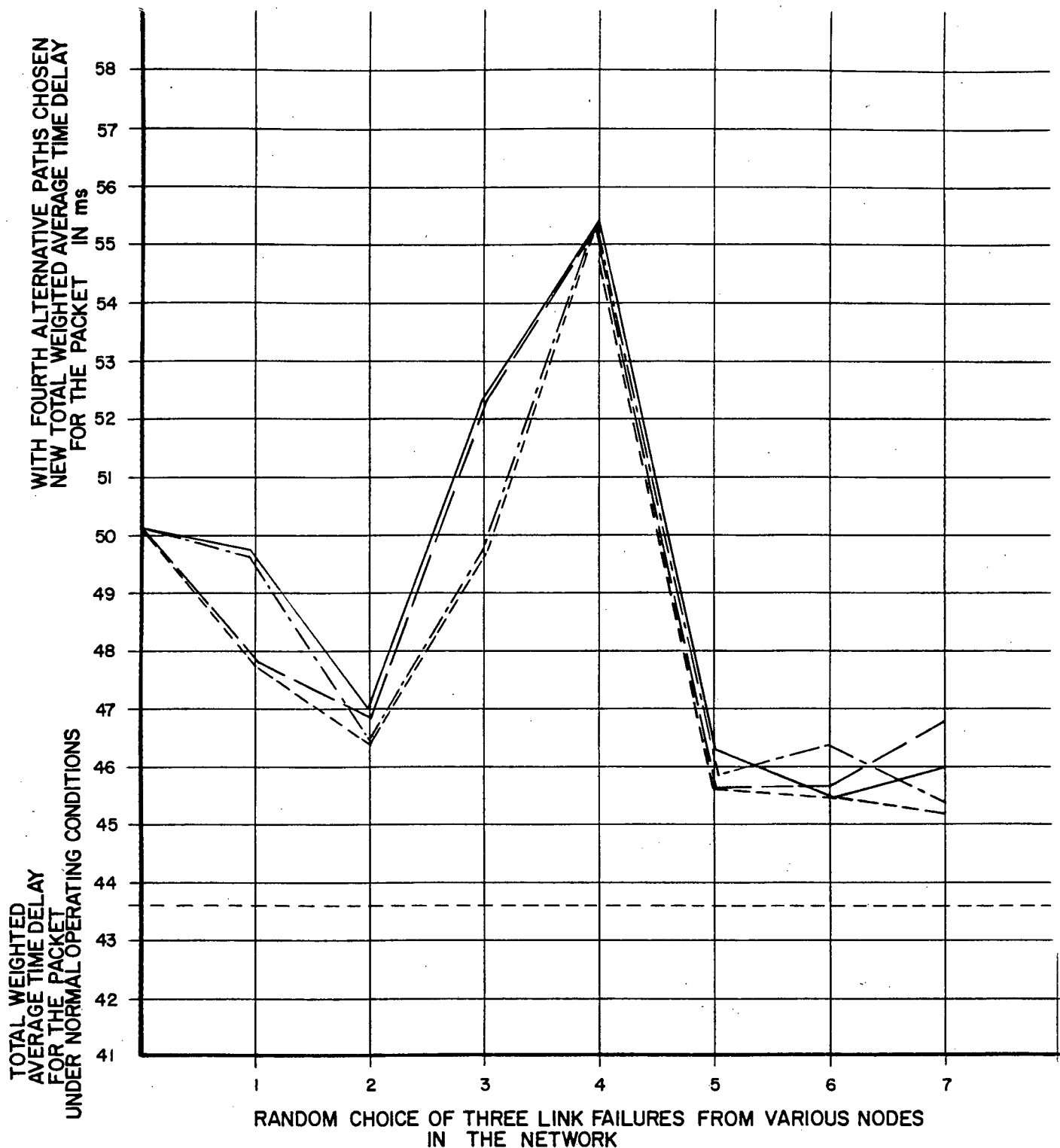
PERCENTAGE INCREASE IN THE TOTAL TRAFFIC FLOWING WITHIN THE NETWORK AFTER THE SECONDARY PATHS HAVE BEEN SELECTED FOR ALL FOUR POSSIBLE COMBINATIONS OF PATHS VERSUS THE LINK WHICH HAS FAILED

FIGURE 10



NEW TOTAL WEIGHTED AVERAGE TIME DELAY WITH A TRAFFIC INPUT OF 172 Kbps UNDER CONDITIONS OF TWO LINK FAILURES FROM VARIOUS NODES IN THE NETWORK AND WITH THE TERTIARY PATHS CHOSEN FOR ALL FOUR COMBINATIONS OF PATHS VERSUS THE RANDOM CHOICE OF TWO LINK FAILURES FROM VARIOUS NODES IN THE NETWORK.

FIGURE 11



- Maximum bandwidth paths
- Minimum estimated time delay paths
- Paths with the lowest utilized primary hops
- Shortest paths

NEW TOTAL WEIGHTED AVERAGE TIME DELAY WITH A TRAFFIC INPUT OF 172Kbps UNDER CONDITIONS OF THREE LINK FAILURES FROM VARIOUS NODES IN THE NETWORK AND WITH THE FOURTH ALTERNATIVE PATHS CHOSEN FOR ALL FOUR COMBINATIONS OF PATHS VERSUS THE RANDOM CHOICE OF THREE LINK FAILURES FROM VARIOUS NODES IN THE NETWORK.

FIGURE 12

FIGURE 10 shows the percentage increase in traffic flow within the network after selecting the alternative (secondary) paths versus the link which has failed. This property is extremely important as mentioned in Chapter 4 and from the result shown in FIGURE 10, it can be seen that under the majority of link failure conditions, the lowest weighted length paths, combination (iv), do provide the user with a combination of alternative paths that add the minimum percentage flow to the overall network flow.

5.4 TERTIARY PATH SELECTION

FIGURE 11 shows the new total weighted minimum estimated time delay T obtained for a packet with a traffic input of 172 Kbit/s when the best combinations of tertiary paths have been chosen after iterations, so that they satisfy either path combination (i), (ii), (iii) or (iv) versus a random choice of situations when two links emanating from assigned nodes have failed. It must be mentioned that the comparison is carried out by assuming that the primary and secondary paths have been chosen so that they are minimum estimated time delay paths.

From these results it can be seen that when two links emanating from a node fail and second alternative paths, that is, the tertiary paths, must be chosen then the combination of the minimum estimated time delay path provides the user with the "optimum" solution.

5.5 FOURTH ALTERNATIVE PATH SELECTION

FIGURE 12 shows the new total weighted minimum estimated time delay T obtained for a packet with a traffic input of 172 Kbit/s when the best combinations of fourth alternative paths have been chosen after iterations so that they

satisfy either path combination (i), (ii), (iii) or (iv) versus a random choice of when three links emanating from assigned nodes have failed.

The comparison is carried out by assuming that the primary, secondary and tertiary paths have been chosen so that they are the minimum estimated time delay paths. Once again the combination of paths with the minimum estimated time delay prove to provide the user with the "optimum" solution.

5.6 TABLED RESULTS

A list of tabled paths for each node in the network configuration given in FIGURE 4(a) to 4(f) is given in their correct coded form in APPENDIX J. If one considers a node more or less geographically in the centre of the network, node 58, then the following observations can be made with respect to the different combinations of second choice paths selected:

(i) the maximum bandwidth paths tend to route the data packets along the longer routes keeping away from the intra DSE links, which have a lower capacity. However, approximately 50% of the routes chosen are the shortest or lowest weighted length paths.

(ii) The minimum estimated time delay paths also route data packets along paths which have physical distances that are longer than that of the shortest paths. The important factor to note, however, is that the shortest or lowest weighted length paths are determined independent of the traffic conditions, whereas the minimum estimated time delay paths are traffic orientated and will tend to route

the data packet away from heavily loaded links. Additionally the average weighted packet time delay obtained by the selection of these paths is better than any of the other combinations of paths and the percentage increase in traffic flow within the network when these paths are selected under fault conditions, compares favourably with that of the combination of shortest paths.

(iii) The combination of paths that send the data packets along the routes with the lowest utilized primary hops use very long routes and do not attain a low average packet time delay.

(iv) The shortest paths route the data packet over those routes which have the lowest weighted path lengths and in the majority of cases over those paths with the least number of intermediate nodes and additional XPROs. Their solution appears to be logically the "optimum" solution to the designer when not considering heavy traffic conditions, however, it is clear from the results shown in the graphs that the average packet delay obtained for the combination of these paths is far from "optimum".

CHAPTER 6

CONCLUSION

6.1 PRESENT STATUS

Results have indicated that, under normal and fault conditions and varying traffic inputs, the minimum average time delay for a packet from source to destination is obtained when the combination of minimum estimated time delay paths have been chosen for the primary, secondary, tertiary and fourth alternative paths. For the primary path analysis, however, the combination of paths selected by the non-bifurcated flow deviation algorithm produced a more 'optimum' value of time delay but only under heavy traffic conditions. At very low traffic inputs, the values of minimum-average time delay of a packet obtained for the combination of minimum estimated time delay paths were not significantly better than those obtained by the combination of shortest paths found.

The routing table for each node in the new proposed SAPONET packet-switched data network were established using a projected traffic-requirement matrix. The present network's traffic requirement was analysed over a one year period and resulted in very low average values for the traffic requirement between all node pairs within the network.

Considering these findings the present situation is such that, since the average input traffic is relatively low, the combination of shortest paths, that is, the combination of lowest weighted length paths would be an acceptable routing policy for all the nodes in the network. The average input traffic entering the network would, however,

have to be monitored and as soon as there is any significant increase in its value then the routing tables for each node in the network should be changed to that of the combination of minimum estimated time delay paths.

6.2 FURTHER RESEARCH

By selecting the shortest paths for the lower traffic inputs and a number of longer paths away from heavily loaded links for the higher traffic inputs, the heuristic routing algorithm presented appears to be adequate under most traffic conditions. There is a need, however, to establish a simulation model to verify the results obtained for the different combination of paths especially at the higher traffic inputs.

A number of bold assumptions have been made throughout this study and further research would be directed so as to include in the routing algorithm, networks with variable packet lengths, links with a high probability of failure and high errors rates where retransmission of the information packets is required and a more accurate analysis of propagation and especially nodal processing delays.

Further research would additionally be undertaken in implementing the non-bifurcated flow-deviation algorithm so that it can determine the secondary, tertiary, etc. paths as well as the primary paths.

6.3 SUMMARY

In this thesis, some fundamental developments in data computer communication networks have been outlined. The tendency to move away from the more conventional circuit-switching scheme to packet switching has been

identified and the importance of the design variables that must be considered in the design of packet-switched computer communication networks stressed. The routing problem has been identified to be of particular importance and the need for a routing algorithm to determine the routing policies for each node in a packet switched computer communication network described.

A network model for a fixed routing policy has been introduced and some of the performance measures, input parameters and constraints that appear in the general design of a computer communication network have been discussed.

The routing problem has been formulated and possible solutions discussed. Basic routing methods have been investigated in some detail. Advantages and shortcomings associated with each of the techniques have been identified and the directory routing method with alternate routing has been identified as a particular requirement and its operating technique has been discussed in detail.

The feasible and best alternative path algorithms which determined some of the input data required for the main routing algorithm, has been developed and presented. The software for these algorithms has been outlined. The modified heuristic routing algorithm has been developed to establish the routing policies for each node in a packet-switched computer communication network. The software for this algorithm has been outlined.

The modified heuristic routing algorithm has been analytically tested on a proposed packet-switched computer communication network and results compared for different combinations of primary, secondary, tertiary and fourth

alternative paths obtained for varying traffic inputs. The heuristic routing procedure presented was also compared with a modified version of an "optimum" routing procedure for the choice of the primary paths only.

Results have been summarized and recommendations made, for present and future "optimum" combination of paths that should be established at each node of the proposed SAPONET packet-switched computer communication network. Finally areas for further research have been discussed.

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APPENDIX A

NETWORK ARCHITECTURE

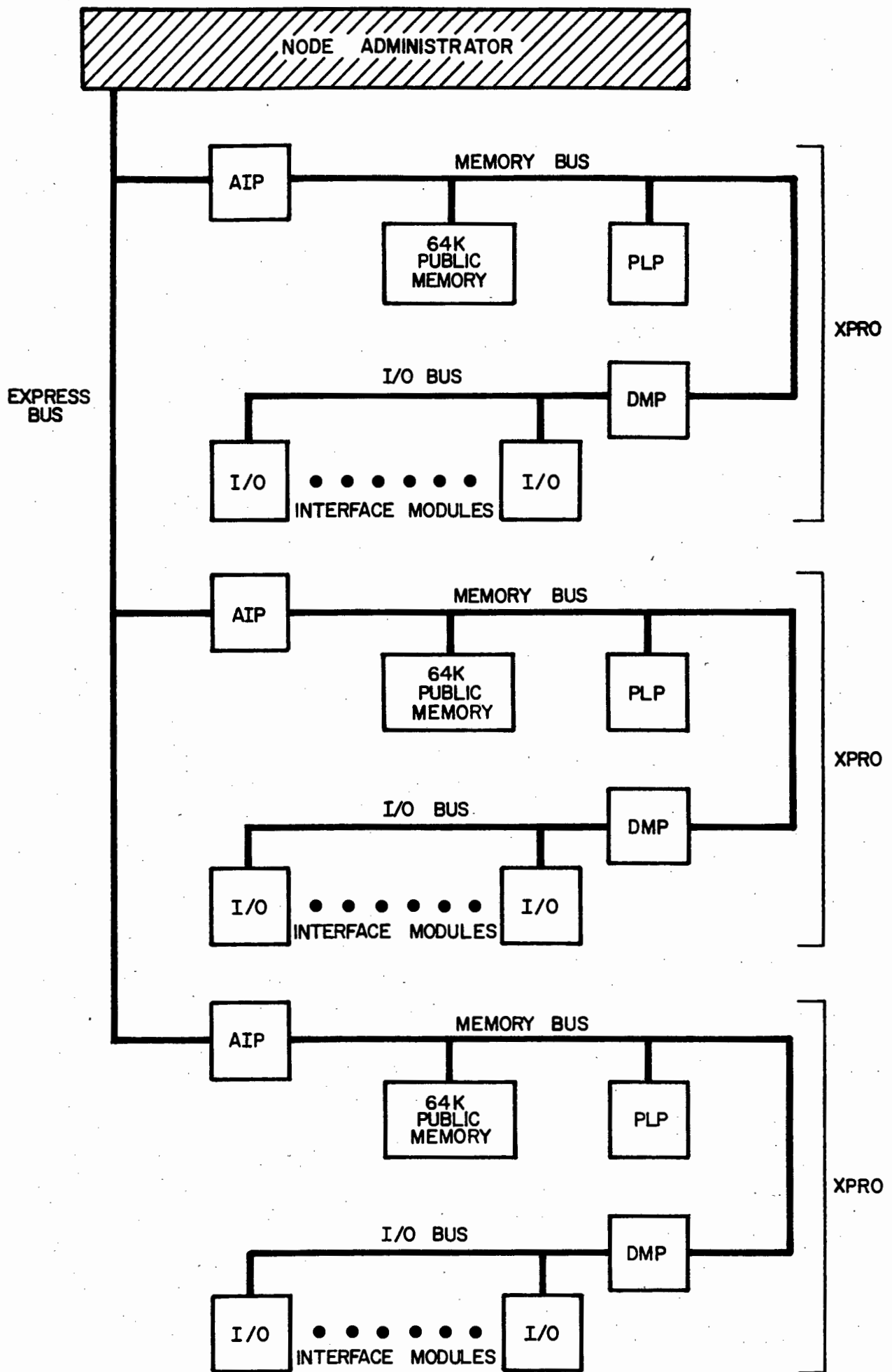
A.1 SWITCHING NODES

Switching nodes or Data Switching Exchanges (DSEs) provides a solution to perhaps the most challenging task that faces network providers today - the interconnection of many user devices from a variety of vendors. This interconnection may take the form of a simple installation serving only a few packet mode devices, or be expanded to a very large multinode network serving over 3500 such devices. The network which is presented to the user has a network access protocol and intranetwork protocol both supporting the virtual circuit technique. Additionally, the DSE system is a virtual circuit packet-switching system supporting the X.25 network access protocol and offers a wide range of user services as well as network design and management features providing an overall efficient and flexible data communications network.

Individual nodes (DSEs) contain a single node administrator and from one to three packet processor units. The packet processor units consists of an Administrator Interface Processor, a Packet Level Processor, a Data Movement Processor, X.25 Public Memory, and various channel interface modules (30, 31). (See FIGURE A-1 for the basic architecture of the 4410 network processor used by SAPONET).

A.1.1 Node Administrator

The node administrator is a minicomputer which verifies the call validity and defines routing connection throughout the



BASIC ARCHITECTURE OF 4410 NETWORK PROCESSOR

FIGURE A-1

network as well as the gathering and formatting of statistical, diagnostic and management reports for the entire node.

A.1.2 Administrator Interface Processor (AIP)

The administrator interface processor connects the packet processor modules to the node administrator.

The packet processor modules (XPROs) mainly consist of an Administrator Interface Processor, a Packet Level Processor, a Data Movement Processor, X25 Public Memory, and various channel interface modules. It provides a path for control information between the packet processor unit and the node administrator.

A.1.3 Packet Level Processor (PLP)

The primary function of the PLP is to handle the control of routing functions of the X25 packet-level protocol (see section A.4) and manage the X25 public memory. Up to seven different routes may be defined. A priority value is assigned to each route, allowing the preferred route to take priority over other routes when they are available. Routes may be defined to as many as 31 other nodes.

A.1.4 Data Movement Processor (DMP)

The data movement processor receives incoming packets and then transfers them to the X25 public memory for storage. The DMP also moves outgoing packets to the interface modules.

A.1.5 X25 Public Memory

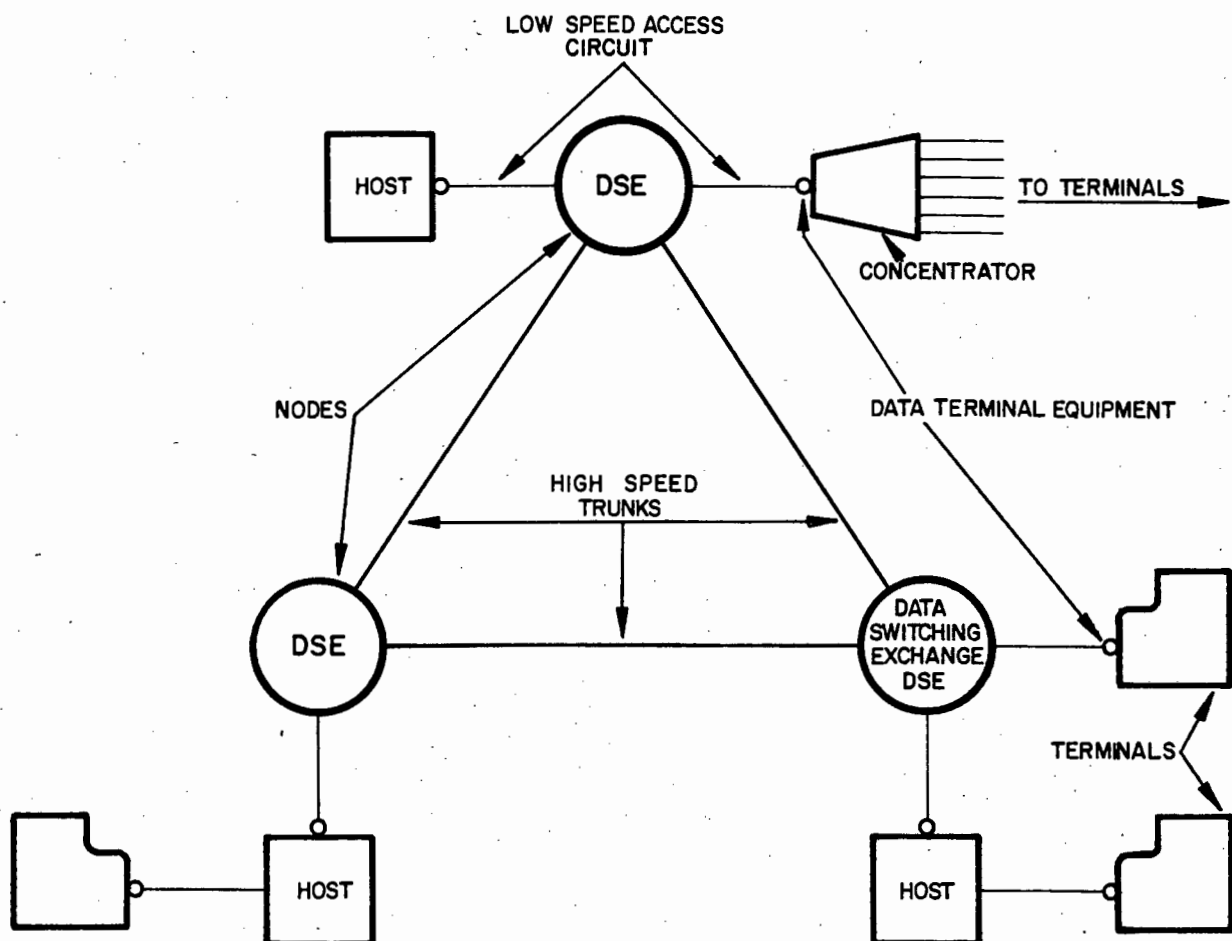
Each X25 packet processor contains a 16-bit 64 kiloword memory which provides buffers for inbound and outbound data packets as well as all the control information needed to handle the X25 protocol.

A.1.6 Interface Modules

Each packet processor unit permits the connection of over 50 packet-mode devices or protocol-translation units commonly referred to as DTE, or data terminal equipment (terminals, hosts, front-end processors, etc). The interface to each module is available for data rates from 1 200 to 19 200 b/s and a single channel-interface V35 module is used for data rates from 19 200 to 64 000 b/s. The interface modules are responsible for handling levels 1 and 2 of the X25 protocol (see section A.4).

A.2 TERMINALS

It is necessary to be able to differentiate between USER (or subscriber) terminals, HOSTS and concentrators all of which can be classified as terminals. A USER terminal is an unintelligent or intelligent keyboard/printer terminal through which the USER can either be connected directly or indirectly via a HOST or concentrator to the switching node by utilizing the basic packet-switching service supporting end-to-end interprocess communication and user services. The HOSTS themselves are machines which support USER application programs and have powerful storage and computing facilities (33). A concentrator supports a number of terminals and is the interface between the terminals and the switching node.



SIMPLE COMPUTER - COMMUNICATION NETWORK

FIGURE A-2

A.3 LINKS

In a packet-switched network the USER has a dedicated access circuit only to the first node in the network where the switching functions are performed (DSE) thereafter trunk-circuits are provided on a shared-demand basis. The access circuits from the user to the DSE and the trunks between DSEs can be described as individual physical data links that are connected in tandem to build up the source to destination communication path.

A simple computer-communication network indicating nodes, terminals and links is shown in FIGURE A-2.

A.4 NETWORK ACCESS PROTOCOL

The network access protocol for the packet switching network model described in FIGURE A-2 is referred to as X25 and is strictly a user-network-interface standard where the USER operates from a set of equipment referred to as the data terminal equipment DTE and the data circuit terminating equipment DCE, which is provided by the network supplier.

The X25 recommendation is essentially divided into three distinct levels of control procedures: (a) Level 1, the physical level which describes the physical, electrical, functional and procedural characteristics to establish, maintain and disconnect the physical link between the terminal DTE and the network (DCE). The level is concerned with the transmission of raw bits over the channel. (b) Level 2, the link level which describes the data link control procedures for data interchange between the terminal and the network operating over a physical level.

(c) Level 3, the packet level specifies the manner in which control information and USER data are structured into packets for transmission between the terminal and the network (32), (34).

2

APPENDIX B

MULTICOMMODITY FLOW DEFINITIONS

Network flow problems have appeared in the management science literature for many years often in connection with logistics problems. However, it has been widely recognized that network flow techniques are applicable to the design and analysis of communication networks as well. The advent of teleprocessing has spurred interest in this area, particularly since the transformation of information between computers gives promise of improved efficiency in the utilization of computer resources (37).

If we consider a network consisting of two nodes then a problem formulation can be defined to find the maximum flow from the source node N_s to the destination node N_d without violating the constraints $X_{ij} \leq b_{ij}$ on the arcs where X_{ij} is the flow on the arc between nodes i and j . If there are many sources and many destinations where the flow from any source can be sent to any destinations and if the restriction is made that the flow from certain sources must not be sent to certain destinations, then the problem is a multicommodity flow problem.

For a computer network, the commodities are packets of data to be transmitted through the network. Element $r_{k,i}$ in the traffic requirement matrix can be viewed as the amount of commodity i that is supplied from node k destined for node i . There are thus N commodities where N is the number of nodes in the network and each node demands exactly one distinct commodity and supplies $N-1$ others.

The multicommodity (MC) flow problem, in this case, consists of finding the routes for all such commodities which minimize a well-defined performance function (cost,

time delay) such that a set of constraints (channel capacities, flows) are satisfied. The most general MC problem can be expressed formally as follows:

Given: A network of N nodes and B arcs.

An $N \times N$ matrix $R = (r_{ij})$, the traffic requirement matrix.

Minimize: $P(\phi)$ where ϕ is the flow configuration and P is a well defined performance function.

APPENDIX C

GRAPH THEORY

A GRAPH consists of a set of elements called NODES and a set of ARCS connecting the nodes. The terms lines, branch, edge and in the context of this study, LINKS (HOPS) are also used in the literature instead of arc. If two nodes are directly connected then they are said to be ADJACENT whereas if they are only indirectly connected via one or more intermediate nodes then they are not adjacent.

Graphs can have the following two types of arcs: (i) a DIRECTED arc indicates that information can flow only in the direction indicated by the arrow in the arc which models simplex or unidirectional channel transmission. (ii) An UNDIRECTED arc indicates that information can flow bothways which models full-duplex channel transmission where flow can be accepted in both directions simultaneously or half-duplex channel transmission where flow can be accepted in either direction but in only one direction at a given instant. A graph containing only directed arcs is called a DIRECTED GRAPH and similarly, a graph containing only undirected arcs is called an UNDIRECTED GRAPH.

The DEGREE (OR VALENCE) of a node is the number of arcs ending there. A PATH is a sequence of adjacent nodes. The LENGTH of a path is the number of arcs it contains. There are no repeated nodes in a path.

If every node is reachable from every other node, that is, if there is a path between every pair of nodes, the graph is said to consist of ONE COMPONENT. A one component graph is also said to be CONNECTED. The ARC CONNECTIVITY between

two nodes X and Y is the minimum number of arcs that must be removed from the graph to disconnect X and Y. Two paths are said to be ARC-DISJOINT if they have no arcs in common and NODE-DISJOINT if they have no nodes in common.

Analogous to the arc connectivity between two nodes is NODE-CONNECTIVITY which is the minimum number of nodes whose removal will disconnect the two nodes. If there are two node disjoint paths between every pair of nodes then such networks are said to be TWO-CONNECTED and if there are three node disjoint paths between every pair of nodes then such networks are said to be THREE-CONNECTED etc.

APPENDIX D

THE FLOW AND NON-BIFURCATED FLOW-DEVIATION ALGORITHMS

D.1 THE FLOW DEVIATION ALGORITHM

The following properties of the optimal routing solution must be mentioned before introducing the FD algorithm (9), (13).

Property 1

The set of MC flows f satisfying the requirement matrix R is a convex polyhedron. The extreme points of such a polyhedron are called "extremal flows" and correspond to shortest route policies where the shortest route policy is a policy that routes each (i, j) commodity along the shortest (i, j) path, evaluated under an arbitrary assignment of lengths to the links.

Property 2

For a given MC flow f , the "length" of a link i can be defined as the partial derivative, i.e.

$$\text{length } i = L_i = \frac{\partial T}{\partial f_i} \quad \text{where } T \text{ is the average time delay expressed in equation 2.4}$$

Let ϕ be the shortest route flow associated with such link lengths and let $\tilde{f} = (1-\lambda)f + \lambda\phi$ be the convex combination of ϕ and f minimizing the delay T . ϕ represents the flow deviation of steepest descent for T and if the flow $\tilde{f}$ is deviated to $\tilde{f} = (1-\lambda)\tilde{f} + \lambda\phi$, the flow $\tilde{f}$ gives a smaller value of T as a hill-descending process. If $T(\tilde{f}) = T(f)$, then $\tilde{f}$ is called stationery and the value of $\tilde{f}$ gives the optimum routing (9), (29).

The algorithm is as follows: (29)

Step 1: Find a feasible starting flow $\tilde{f}^0$, Let $P=0$ where P is the number of iterations.

Step 2: Compute $\tilde{\phi}(P)$, the shortest route flow corresponding to $li(P) = (\partial T / \partial f_i) f = f(P)$ for all $i=1,2,\dots,b$ where b is the number of links.

Step 3: A value of λ is found which minimizes
 $T [(1-\lambda)\tilde{f}^{(P)} + \lambda\tilde{\phi}(P)]$
 Let $f^{(P+1)} = (1 - \lambda) \tilde{f}^{(P)} + \lambda \tilde{\phi}(P)$

Step 4: If $T(f^{(P)}) - T(f^{(P+1)}) < \epsilon$ STOP : $f^{(P)}$ is the optimum flow, otherwise let $P=P+1$ and GO TO STEP 2.

An important detail to note about the above FD method is that it recommends that commodities should be sent along more than one route which is fine if the network operates on a datagram protocol, but for virtual circuit operation a slightly different FD method is required and is explained in the following section.

D.2 THE ~~NON-BIFURCATED~~ FLOW-DEVIATION ALGORITHM

An MC flow is defined as non-bifurcated if each commodity flows along one route only. The introduction of this constraint reduces the set of feasible MC flows to a discrete set. Continuous techniques, like the FD method explained in D.1 cannot be used to solve the routing problem and therefore an efficient sub-optimum technique is required. In the case of large networks and where the elements r_{ij} of the requirement matrix R is not highly diversified from one another, a modification of the FD method can be successfully applied (36). If we assume the following:

- (i) "length" of link i can be defined as the partial derivative i.e.

$$\text{length } i = L_i = \frac{\partial T}{\partial f_i} \quad \text{where } T \text{ is the average time delay expressed in equation 2.4.}$$

- (ii) ϕ is the shortest routes associated with such link lengths.

- (iii) flow $\tilde{f}$ is non-bifurcated.

- (iv) that commodity (i,j) flows on route π_{ij} .

- (v) π'_{ij} is the shortest (i,j) route.

The modified FD method deviated a proper amount λr_{ij} ($\lambda=1$), of (i,j) commodity from π_{ij} to π'_{ij} such that the performance $T(\lambda) = T[(1-\lambda)\tilde{f}^{(P)} + \lambda\phi^{(P)}]$ is minimized. Where $\tilde{f}$ contains π_{ij} and ϕ contains π'_{ij} . The algorithm is as follows:

Step 1: Let $\tilde{f}^0$ be a starting feasible non-bifurcated flow, set $P=0$ where P is the number of iterations.

Step 2: Compute SR ($\tilde{f}^{(P)}$), the shortest routes corresponding to $l_i^{(P)} = \partial T / \partial f_i$ $f = \tilde{f}^{(P)}$ for all $i = 1, 2, \dots, b$ where b is the number of links.

Step 3: Set $\tilde{g} = \tilde{f}^{(P)}$
For each commodity (i,j) :

- 3 (a) Let ϕ be the flow configuration obtained from $\tilde{g}$ by deviating commodity (i,j) to the shortest route π'_{ij} given by SR ($\tilde{f}^{(P)}$)
- 3 (b) If ϕ is feasible and $T(\phi) < T(\tilde{g})$ GO TO 3 (c), otherwise GO TO 3 (d).
- 3 (c) $\tilde{g} = \phi$

3 (d) If all commodities (ij) have been processed, GO TO 4, otherwise, GO TO 3(a).

Step 4: If $\tilde{g} = \tilde{f}^{(P)}$, STOP. The FD method cannot improve the non-bifurcated solution any further, otherwise, let $\tilde{f}^{(P+1)} = \tilde{g}$ and, let $P = P+1$ and GO TO STEP 2.

Note:- This algorithm only determines the primary paths between all node pairs in the network.

APPENDIX E

DEFINITION OF TERMS USED IN THE ALGORITHMS

- i - Is the source node in a path, where i can be equal to any value from 1 to N but $\neq j$, where N is the number of nodes in the network.
- j - Is the destination node in a path, where j can be equal to any value from 1 to N but $\neq i$.
- (i,j) - Is a node pair combination where i is the source node and j is the destination node and $i \neq j$.
- ij - Is the path between source node i and destination node j.
- (i₀,i₁) - Is the primary hop of path ij.
- (i₁,i₂) - Is the secondary hop of path ij.
- ⋮ ⋮
- (i_{k-1},i_k) - Is the kth hop of path π_{ij} (if $i_1 = j$ then path π_{ij} is the direct path between nodes i and j).
- $B\pi_{ij}$ - Are the best alternative paths between all source and destination node-pair combinations (i,j) in ascending order of weighted length.

- $A\pi_{ij}$ - "Affected path" between nodes i and j . For the primary path algorithm these are two or more paths between specific source-to-destination node pairs (i,j) each connected via an equal number of intermediate nodes and equal lowest "weighted" distance. For the secondary path algorithm these are the primary paths whose primary hops are affected by a link down. For the tertiary path algorithm these are the source to destination node pair paths whose primary and secondary paths primary hops are affected by the two links that are down. For the fourth alternative path algorithm these are the source to destination node pair paths whose primary, secondary and tertiary path primary hops are affected by the three links that are down.
- $SR\pi_{ij}$ - Is the path taken between source node i and destination node j when any hop other than the primary hop of a primary, secondary or tertiary path chosen has been affected by disconnected links.
- WN - Is the "working node" where for the tertiary path algorithm it is defined as a node (with a valence of 3) in the network which has three or more other nodes connected directly to it and for the fourth alternative path algorithm it is defined as a node (with a valence of 4) in the network which has four or more other nodes connected directly to it.

APPENDIX F

FEASIBLE PATH ALGORITHM

The following is a basic outline of the program used to determine all the feasible paths between all node pairs within a network:

Program:

- Step 1 : Read in the input data as follows: number of nodes in the network (N), node weight in kilometres for each intermediate node in a path, XPRO weight in kilometres for each additional XPRO that the data packet traverses on its path through an intermediate node, the maximum acceptable number of hops in a path (MH), maximum acceptable weighted path length in kilometres, the node configuration matrix and the link matrix.
- Step 2 : Assign a new source node and set all parameters to initial values. If all nodes have been assigned as source nodes then GO TO STEP MH+5.
- Step 3 : Find the next node that is directly connected to the assigned source node. If all nodes that are directly connected to the assigned source node have been found then GO TO STEP 2. Store the feasible path found together with its physical and weighted path lengths into the assigned source nodes temporary file. Assign the destination node of the feasible path found as "working node 1" (a reference node used as an intermediate node for the next feasible path).

Step 4 : Find the next node that is directly connected to working node 1. If all nodes that are directly connected to working node 1 have been found then GO TO STEP 3. Assign the node that is directly connected to working node 1 as working node 2. If the path found between the assigned source node and working node 2 is a feasible path then store the path information together with the feasible path physical and weighted path lengths in the assigned source node temporary file.

:
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:

Step K : Find the next node that is directly connected to working node (K-3). If all nodes that are directly connected to working node (K-3) have been found then GO TO STEP (K-1). Assign the node that is directly connected to working node (K-3) as working node (K-2). If the path found between the assigned source node and working node (K-2) is a feasible path then store the path information together with the feasible path physical and weighted lengths in the assigned source node temporary file.

:
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:

Step MH+3 : Find the next node that is directly connected to working node (MH-1). If all nodes that are directly connected to working node (MH-1) have been found then GO TO STEP (MH+1).

Assign the node that is directly connected to working node (MH-1) as working node (MH). If the path found between the assigned source node and working node (MH) is a feasible path then store the path information together with the feasible path physical and weighted lengths in the assigned source nodes temporary file.

Step MH+4 : GO TO STEP MH+3

Step MH+5 : Sort each node's temporary file of feasible paths in ascending order of weighted length and transfer sorted data to a permanent data file.

Step MH+6 : STOP

In the above program, MH is the maximum number of "hops" input by the routing manager and K is an integer that is greater than 4 but less than MH+3. In the context of the feasible path algorithm the "working node" is defined as the destination node of the last feasible path found from the assigned source node and is used as an intermediate node for the next feasible path from the assigned source node.

It is possible for the feasible path algorithm to be used by any general user who wishes to determine all paths between all possible node pairs within a network. The weighing factors in his network could be different to those defined in the examples shown in FIGURE 4(g) and in the case where, for example, the additional processing stages are not required then the input data would be such that the additional XPRO weight (XPROWT) and all entries of the node configuration matrix would be set to zero.

APPENDIX G

BEST ALTERNATIVE PATH ALGORITHM

The following is a basic outline of the program used to determine the best alternative paths between all node pairs within a network.

Program:

Step 1 : Initialize and set all parameters to zero.

Step 2 : Read in the node configuration matrix.

Step 3 : Read in the next feasible path. If all feasible paths have been read in then GO TO STEP 5.

Step 4 : If the primary hop of the feasible path between the source and destination node is an alternative to any of the previous path(s) found, then store path information together with the weighted length of the path in the data file.

However, in those cases where there are two possible alternative paths with the same primary hop and weighted length then the path with the least number of XPROS traversed at the intermediate node is stored in the data file. These are the best alternative paths.
GO TO STEP 3.

Step 5 : STOP

APPENDIX H

MODIFIED HEURISTIC ROUTING ALGORITHM

The basic outline of the modified heuristic routing algorithm used to determine the "optimal" routing tables for the network is as follows:

H.1 PROGRAM

- Step 1 : Set all parameters to their initial values.
- Step 2 : Read in the number of nodes, the number of links, path type, maximum acceptable utilization factor and whether the modified combination of paths is required.
- Step 3 : Read in the node configuration, link capacity and link matrices.
- Step 4 : Read in the high medium and low traffic-carrying nodes as well as their respective average-to-peak traffic ratios.
- Step 5 : Read in and store the traffic matrix in memory.
- Step 6 : Read in the best alternative paths for all source-to-destination node pair combinations. If the path type requested is the "shortest path" then store the first alternative path (lowest weight length path) as the primary path, the second as the secondary path, etc for all source to destination node pair combinations. Store these paths in their respective files, print-out the results then GO TO STEP 12. If any path type

other than the shortest path is selected then store in memory all the best alternative paths read in.

Step 7 : Start Primary Path Algorithm (see section H.1.1) to determine primary paths between all node pairs.

Step 8 : Read in all combinations of one link down from each node in the network and start the Secondary Path Algorithm (see section H.1.2) to determine all the secondary paths between all node pairs.

Step 9 : Read in all combinations of two links down from each node in the network with more than two links and start the Tertiary Path Algorithm (see section H.1.3) to determine all the tertiary paths between these nodes and all other nodes in the network.

Step 10 : Read in all combinations of three links down from each node in the network with more than three links and start the Fourth Alternative Path Algorithm (see section H.1.4) to determine all the fourth alternative paths between these nodes and all other nodes in the network.

Step 11 : Store the source to destination node path information for all possible node pair combinations in primary, secondary, tertiary and fourth alternative path files.

Step 12 : STOP.

In the following sections a more detailed explanation of the Algorithms mentioned in STEP 7 to STEP 10 is given

together with an explanation of a heuristic algorithm that is implemented where all the decision making is made for the choice of the primary, secondary, tertiary, and fourth alternative paths.

H.1.1 Primary Path Algorithm

Step 1 : Read in the best alternative paths.

Step 2 : For all possible source to destination node pair combinations, those source to destination paths that are directly connected and those paths that are connected via the lowest "weighted" distance (shortests paths) are stored in memory locations set aside for the "primary paths". (It is assumed that those paths which are directly connected have the lowest "weighted" distances and the next lowest "weighted" lenght paths are the paths with the least number of intermediate nodes. In the case of the example network shown in FIGURE 4(a) this assumption is true.)

Step 3 : Where there are two or more paths between a source-to-destination node pair that have an equal lowest weighted path length (connected with an equal number of intermediate nodes), then these paths are stored in memory locations set aside for "affected paths".

Step 4 : The end-to-end traffic is routed along those source to destination paths stored in memory locations set aside for "primary paths". This in effect assigns traffic flows f_i 's ($i=1,2,\dots,P$), in both directions, across those links in the primary paths.

Step 5 : If there are any paths stored in memory locations set aside for "affected paths" then they are now considered and for each affected source to destination node pair, the best primary path is chosen by implementing the Modified Heuristic Algorithm detailed in section H.1.5 and these paths are then added to those paths stored in memory locations set aside for primary paths, otherwise the utilization factor and the traffic flow on each link is checked whether within limits (indication is given if they are not within the limits).

H.1.2 Secondary Path Algorithm

Step 1 : The end-to-end traffic is routed along those paths found in the "primary path algorithm" that, in effect, assign flows f_i 's ($i=1,2,\dots,P$), in both directions, across those links in the network utilized by these primary paths.

Step 2 : The link to be disconnected (information obtained from the link matrix) is read in and all those primary paths whose primary hops are affected by the disconnected link are stored in memory location set aside for "affected paths".

Step 3 : Those primary paths whose hops other than their primary hops (secondary, tertiary, etc. hops, that is, the second, third, etc. hop in a path) that are affected by the disconnected link are determined. The traffic flow that these paths generate is added to the total traffic flow that is required to flow over the direct path found in step 2.

- Step 4 : The traffic flow generated on each link (λ_i) by those paths saved in the memory location set aside for "affected paths" is removed from the network. This in effect produces new traffic flows accross some of the links in the network and zero traffic flow, in both directions, across the disconnected link.
- Step 5 : The affected paths are now considered and for each affected source to node pair combination the secondary paths are chosen from the best alternative paths by implementing the Modified Heuristic Algorithm.
- Step 6 : These paths are stored in a memory location set aside for secondary paths.
- Step 7 : The process is repeated until all links have been disconnected, in turn, and all secondary paths selected.

H.1.3 Tertiary Path Algorithm

- Step 1 : The end-to-end traffic is routed along those paths found in the "primary path algorithm". This in effect assigns flows f_i 's ($i=1,2,\dots,P$), in both directions, across those links in the network utilized by these primary paths.
- Step 2 : The next working node WN (defined here as a node in the network that has three or more other nodes connected directly to it) and two nodes connected directly to the working node, which represent the co-ordinates of the links to be disconnected, are read in.

Step 3 : If the modified combination of paths (see input data in section 4.5) has been requested by the user or if the working node has only three links then the best alternative path with the lowest weighted length between the working node and all other nodes is stored in the memory location set aside for tertiary paths, then GO TO STEP 2, otherwise assign a source and node pair combination and continue to STEP 4.

Step 4 : If all primary paths have been considered then GO TO STEP 7. The primary path between the assigned source and destination node pair combination is considered and if it is affected by the disconnected links then the traffic flow which this path generates is removed from the network and STEP 5 started, otherwise the next source-to-destination node pair is assigned and STEP 4 repeated.

Step 5 : If the primary hop of the primary path considered is affected by the disconnected links then the secondary path is found and if it is not affected by the disconnection then the traffic flow generated by the secondary path is added to the network flow, a new source and destination node pair combination is assigned and STEP 4 repeated, otherwise if the primary hop is not affected GO TO STEP 6. If the primary hop of the secondary path is affected by the disconnected links, then the path information is stored in memory location set aside for "affected paths", otherwise if the secondary path is not affected by the disconnected links then the traffic flow generated by this path is added to the network flow. If any hop other than the primary hop of the secondary path is affected by the disconnected links then

the initial part of the path information is saved so as to include the primary hop and, if possible, the secondary hop of the secondary path. The last node in this path is assigned as the new source node and the path that the data packet would take from the new source node to the destination node is found. This path information is added to the initial part of the path saved to produce a path from the original source node to the destination node, which is then saved in the memory set aside for "stored paths". A new source and destination node is assigned and STEP 4 repeated.

- Step 6 : If any hop other than the primary hop of the path considered is affected by the disconnected links then the initial part of the path is saved as far as the data packet can be transmitted before encountering the disconnected links. The last node is assigned as the new source node and the path found that the data packet would take from the new source node to the destination node. This path information is added to the initial part of the path to produce a path from the original source node to the destination node which is then saved in the memory location set aside for "stored paths". A new source and destination node is assigned and STEP 4 repeated.
- Step 7 : Once all primary paths have been considered the traffic flow generated by all the paths stored in the memory location set aside for "stored paths" is added to the network and this together with the other paths assigned in STEP 5 effectively assigns new traffic flow across some of the links with zero traffic flow, in both directions, across the disconnected links.

- Step 8 : The affected paths are now considered and for each affected source to destination node pair combination the tertiary paths are chosen from the best alternative paths by implementing the Modified Heuristic Algorithm.
- Step 9 : These paths are then stored in the memory location set aside for tertiary paths.
- Step 10 : The process is repeated until all two link combinations have been disconnected and all tertiary paths selected.

H.1.4 Fourth Alternative Path Algorithm

- Step 1 : The traffic requirement is routed along those paths found in the primary path algorithm. This in effect assigns flows f_i 's ($i=1,2,\dots,P$), in both directions, across those links utilized by these primary paths in the network.
- Step 2 : The working node WN (defined here as a node in the network that has four or more other nodes connected directly to it) and three nodes connected directly to the working node, which represent the co-ordinates of the three links to be disconnected, are read in.
- Step 3 : If the modified combination of paths has been requested by the user or if the working node has only four links then the best alternative path with the lowest weighted length between the working node and all other nodes is stored in the memory location set aside for fourth alternative paths, then GO TO STEP 2, otherwise assign a source and node pair combination and continue to STEP 4.

- Step 4 : If all primary paths have been considered then GO TO STEP 7. The primary path between the assigned source and destination node pair combination is considered and if it is affected by the disconnected links then the traffic flow, which this path generates, is removed from the network and STEP 5 started, otherwise the next source to destination node pair is assigned and STEP 4 repeated.
- Step 5 : If the primary hop of the primary path considered is affected by the disconnected links then the secondary path is found and if it is not affected by the disconnection then the traffic flow generated by the secondary path is added to the network flow, a new source and destination node pair combination is assigned and STEP 4 repeated, otherwise if the primary hop is not affected GO TO STEP 6. If the primary hop of the secondary path is affected by the disconnected links then the tertiary path is found and if the primary hop of the tertiary path is also affected then the path information is stored in the memory location set aside for "affected paths", otherwise if the tertiary path is not affected by the disconnected links then the traffic flow generated by this path is added to the network flow. If any hop, other than the primary hop of the secondary or tertiary paths, found is affected by the disconnected links, the initial part of the path information is saved so as to include the primary hop and, if possible, the secondary hop of the secondary or tertiary path. The last node in this path is assigned as the new source node and the actual path taken by the data packet from the new source node to the destination node is found. This path information is added to the initial part of the path saved to produce

a path from the original source node to the destination node, which is then saved in the memory location set aside for "stored paths". A new source and destination node-pair combination is assigned and STEP 4 repeated.

Step 6 : If any hop other than the primary hop of the considered primary path is affected by the disconnected links, the initial part of the path information is saved as far as the data packet can be transmitted before encountering the disconnected links, the last node is assigned as the new source node and the path found that the data packet would take from the new source node to the destination node. This path information is then added to the initial part of the path saved to produce a path from the original source node to the destination node which is then saved in the memory location set aside for "stored paths". A new source and destination node-pair combination is assigned and STEP 4 repeated.

Step 7 : Once all primary paths have been considered, the traffic flow generated by all the paths stored in the memory location set aside for "stored paths" is added to the network and this together with the other paths assigned in STEP 5 assigns new traffic flows across some of the links in the network with zero traffic flow in both directions across the disconnected links.

Step 8 : The affected paths are now considered and for each affected source-to-destination node-pair combination, the fourth alternative paths are chosen from the best alternative paths by implementing the Heuristic Algorithm.

- Step 9 : These paths are then stored in the memory location set aside for fourth alternative paths.
- Step 10 : The process is repeated until all three link combinations have been disconnected and all fourth alternative paths selected.
- Step 11 : The primary, secondary, tertiary and fourth alternative paths are stored in their respective permanent files.
- Step 12 : Stop routing algorithm.

H.1.5 Modified Heuristic Algorithm

- Step 1 : An affected path between source node i and destination node j is considered. In the case of primary path processing those affected paths with the same source and destination nodes are considered.
- Step 2 : The Modified Heuristic Algorithm is processed as explained in chapter 4 and either the maximum bandwidth, minimum estimated average time delay, or lowest utilized primary hop paths determined.

If no alternative path is found for any one of the three cases because the capacity constraint has not been met, then this fact is indicated to the user. In order to allow the routing algorithm to continue and find any further cases where constraints are not met, the longest

weighted length path is chosen from the subset of best alternative paths Π_k and the traffic is routed over this path. The user would, however, have to adjust his network - increase capacities of links so that all the constraints are met and then run the algorithm again.

- Step 5 : The next affected path is considered and new source node i and destination node j assigned. In the case of primary path processing the next set of affected paths with the same source and destination nodes are considered. STEP 2 to STEP 5 is repeated until all possible affected paths have been processed.
- Step 6 : The total average packet time delay for the network T (see section 3.2 for the formula - for this calculation the propagation and nodal processing delay is fixed) is calculated, which is dependent on the stored traffic flow and the traffic flow generated by the paths selected in STEP 2 to STEP 5.
- Step 7 : If there is more than one affected path then the order of processing the affected paths is rearranged so that the affected path that was processed first is now processed last.
- Step 8 : All required parameters are reset to their initial values and STEP 1 to STEP 7 is repeated. The newly calculated total average time delay for the network T is compared with the previous minimum value for T . If the new selection of paths does produce an improved value for T then these paths and the value of T are saved. The process is repeated until the order of processing the affected paths is such that the

affected path that was processed first is back at the top of the queue.

Step 9 : Dependent on which algorithm is being implemented and if all primary or secondary or tertiary paths have been selected for all possible source to destination node pair combinations, then these paths are removed from memory saving the best alternative paths and the algorithm for determining the next set of paths is started, otherwise RETURN TO the algorithm which is being implemented.

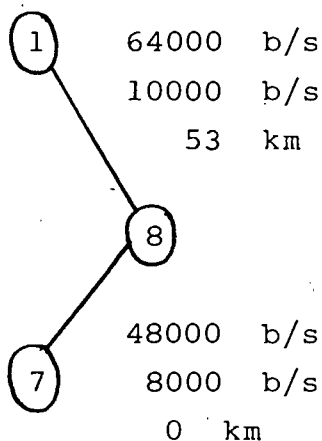
APPENDIX I

AVERAGE TIME DELAY CALCULATIONS

An example of a simple three node network will be used to demonstrate how the average message time delay in the network from any source to destination node is calculated. The equation used is a rearrangement of equation 2.4 given in Chapter 2:

$$T = \frac{1}{\lambda} \sum_{i=1}^b f_i \left[\frac{1}{c_i - f_i} + \lambda_i (P_{Di} + N_{PDi}) \right]$$

If one considers a simple three node network shown below



The capacity of the link between node 1 and 8 is 64 000 b/s and the average flow f on that link is 10 000 b/s.

The physical distance between the two nodes is 53kms. The capacity of the link between node 8 and node 7 is 48 000 b/s and the average flow f on that link is 8 000 b/s. The

physical distance between the two nodes is 0 kms, that is, the nodes are situated at the same location.

The total traffic input into the network is

$$\frac{172000 \text{ b/s}}{1024 \text{ b/p}} = 170 \text{ p/s}$$

(for the SAPONET model the traffic input is given in

bits per second since the average packet length $\frac{1}{1024}$ is 1024 bits per packet, however a conversion factor is

used in the main algorithm to convert to packets per second).

Detailed calculations for the propagation and nodal processing delays have not been made throughout this study, however, the following assumptions have been made:

Propagation delay is 1ms per 1 000KM.

Nodal processing delay is 1ms plus the number of additional XPROs traversed at the intermediate nodes. For the above example if we take node 8 as the intermediate node and if we go from node 1 through node 8 to node 7 then by referring to FIGURE 4 (c) one can see that one must go via the intermediate node plus one additional XPRO, therefore, the nodal processing delay at node 8 would be 2ms. The three node network has been extracted from the seventeen node SAPONET network for simplicity of calculation of the average message delay in the network from any source to destination node.

With these assumptions and given data, the calculations are carried out as follows:

$$T = \frac{1}{170} \left[10000 \left(\frac{1000}{64000-10000} + \frac{1}{1024} \left(\frac{53}{1000} + 2 \right) \right) + \right.$$

$$\left. 8000 \left(\frac{1000}{48000-8000} + \frac{1}{1024} (0 + 1) \right) \right] = 2,43 \text{ms/p.}$$

APPENDIX J
-----TABLED RESULTS

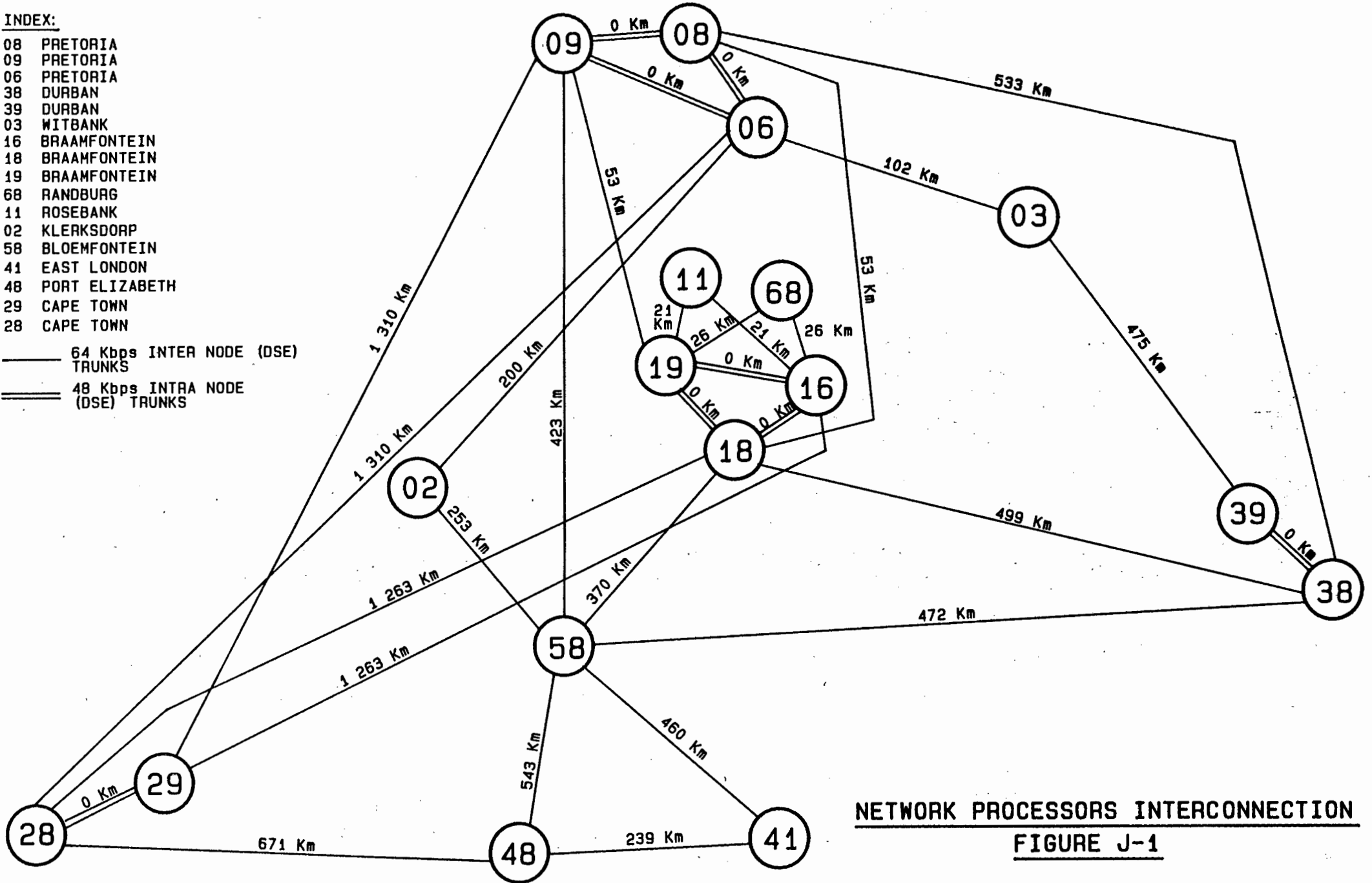
The routing tables for each node in the network shown in FIGURE J-1 (FIGURE 4(a) with the actual codes indicated for each node in the network) for the four different possible path combinations is given in this APPENDIX. The results were obtained using a total traffic input of approximately 200 Kbit/s.

The results from the non-bifurcated flow deviation algorithm have not been tabulated as only the primary paths were determined when this algorithm was run. Since the primary and secondary paths for the modified combination of paths are the same as the results tabulated, their results have not been tabulated.

INDEX:

- 08 PRETORIA
- 09 PRETORIA
- 06 PRETORIA
- 38 DURBAN
- 39 DURBAN
- 03 WITBANK
- 16 BRAAMFONTEIN
- 18 BRAAMFONTEIN
- 19 BRAAMFONTEIN
- 68 RANDBURG
- 11 ROSEBANK
- 02 KLERKSDORP
- 58 BLOEMFONTEIN
- 41 EAST LONDON
- 48 PORT ELIZABETH
- 29 CAPE TOWN
- 28 CAPE TOWN

—— 64 Kbps INTER NODE (DSE) TRUNKS
==== 48 Kbps INTRA NODE (DSE) TRUNKS



NETWORK PROCESSORS INTERCONNECTION
FIGURE J-1

MAXIMUM BANDWIDTH PATHS

DESTINATION		ROUTING FROM SYSTEM 08 IN PRETORIA																
OSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE				
PRETORIA	08																	
PRETORIA	09	09				38	58	09		18	19	09		06	09			
PRETORIA	06	06				38	39	03	06	09	06			18	19	09	06	
BRAAMFONTEIN	16	18	16			38	18	16		06	09	19	16	09	19	16		
BRAAMFONTEIN	18	18				38	18			09	19	18		06	09	19	18	
BRAAMFONTEIN	19	18	19			06	09	19		38	18	19		09	19			
CAPE TOWN	28	06	28			38	18	28		18	28			09	29	28		
CAPE TOWN	29	09	29			06	28	29		38	18	28	29	38	18	28	29	
DURBAN	38	38				18	38			06	03	39	38	09	58	38		
DURBAN	39	38	39			06	03	39		18	38	39		09	06	03	39	
PORT ELIZABETH	48	18	58	48		38	58	48		06	09	58	48	09	58	48		
BLOEMFONTEIN	58	18	58			38	58			09	58			06	09	58		
EAST LONDON	41	18	58	41		38	58	41		09	58	41		06	09	58	41	
KLERKSDORP	02	06	02			38	58	02		18	58	02		09	06	02		
WITBANK	03	06	03			38	39	03		09	06	03		18	19	09	06	03
RANDBURG	68	18	19	68		38	18	16	68	09	19	68		06	09	19	68	
ROSEBANK	11	18	19	11		38	18	19	11	09	19	11		06	09	19	11	

MINIMUM ESTIMATED TIME DELAY PATHS

DESTINATION		ROUTING FROM SYSTEM 08 IN PRETORIA																
OSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE				
PRETORIA	08																	
PRETORIA	09	09				38	58	09		06	09			18	19	09		
PRETORIA	06	06				38	39	03	06	09	06			18	19	09	06	
BRAAMFONTEIN	16	18	16			38	18	16		09	19	16		06	09	19	16	
BRAAMFONTEIN	18	18				38	18			09	19	18		06	09	19	18	
BRAAMFONTEIN	19	09	19			18	19			38	18	19		06	09	19		
CAPE TOWN	28	06	28			18	28			38	18	28		09	29	28		
CAPE TOWN	29	09	29			18	28	29		06	28	29		38	18	28	29	
DURBAN	38	38				18	38			06	03	39	38	09	58	38		
DURBAN	39	38	39			06	03	39		18	38	39		09	06	03	39	
PORT ELIZABETH	48	18	58	48		38	58	48		06	09	58	48	09	58	48		
BLOEMFONTEIN	58	09	58			38	58			18	58			06	09	58		
EAST LONDON	41	18	58	41		38	58	41		06	09	58	41	09	58	41		
KLERKSDORP	02	06	02			38	58	02		18	58	02		09	06	02		
WITBANK	03	06	03			38	39	03		09	06	03		18	19	09	06	03
RANDBURG	68	09	19	68		38	18	16	68	06	09	19	68	18	19	68		
ROSEBANK	11	18	19	11		09	19	11		06	09	19	11	38	18	19	11	

PATHS WITH THE LOWEST UTILIZED PRIMARY HOPS

DESTINATION		ROUTING FROM SYSTEM 08 IN PRETORIA																
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE				
PRETORIA	08																	
PRETORIA	09	09				38	58	09		06	09			18	19	09		
PRETORIA	06	06				38	39	03	06	18	19	09	06	09	06			
BRAAMFONTEIN	16	18	16			38	18	16		09	19	16		06	09	19	16	
BRAAMFONTEIN	18	18				38	18			06	09	19	18	09	19	18		
BRAAMFONTEIN	19	18	19			38	18	19		09	19			06	09	19		
CAPE TOWN	28	06	28			38	18	28		18	28			09	29	28		
CAPE TOWN	29	09	29			38	16	28	29	06	28	29		18	28	29		
DURBAN	38	38				06	03	39	38	09	58	38		18	38			
DURBAN	39	38	39			18	38	39		06	03	39		09	06	03	39	
PORT ELIZABETH	48	18	58	48		38	58	48		09	58	48		06	09	58	48	
BLOEMFONTEIN	58	18	58			38	58			09	58			06	09	58		
EAST LONDON	41	18	58	41		38	58	41		09	58	41		06	09	58	41	
KLERKSDORP	02	06	02			18	58	02		09	06	02		38	58	02		
WITBANK	03	06	03			38	39	03		09	06	03		18	19	09	06	03
RANDBURG	68	18	19	68		38	18	16	68	09	19	68		38	18	19	68	
ROSEBANK	11	18	19	11		06	09	19	11	09	19	11		38	18	19	11	

SHORTEST PATHS

DESTINATION		ROUTING FROM SYSTEM 08 IN PRETORIA																
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE				
PRETORIA	08																	
PRETORIA	09	09				06	09			18	19	09		38	58	09		
PRETORIA	06	06				09	06			18	19	09	06	38	39	03	06	
BRAAMFONTEIN	16	18	16			09	19	16		06	09	19	16	38	18	16		
BRAAMFONTEIN	18	18				09	19	18		38	18			06	09	19	18	
BRAAMFONTEIN	19	18	19			09	19			06	09	19		38	18	19		
CAPE TOWN	28	06	28			18	28			09	29	28		38	18	28		
CAPE TOWN	29	09	29			06	28	29		18	28	29		38	18	28	29	
DURBAN	38	38				18	38			09	58	38		06	03	39	38	
DURBAN	39	38	39			18	38	39		06	03	39		09	06	03	39	
PORT ELIZABETH	48	18	58	48		18	58	48		06	09	58	48	38	58	48		
BLOEMFONTEIN	58	09	58			18	58			06	09	58		38	58			
EAST LONDON	41	18	58	41		09	58	41		06	09	58	41	38	58	41		
KLERKSDORP	02	06	02			09	06	02		18	58	02		38	58	02		
WITBANK	03	06	03			09	06	03		38	39	03		18	19	09	06	03
RANDBURG	68	18	19	68		09	19	68		06	09	19	68	38	18	16	68	
ROSEBANK	11	18	19	11		09	19	11		06	09	19	11	38	18	19	11	

MAXIMUM BANDWIDTH PATHS

DESTINATION		ROUTING FROM SYSTEM 09 IN PRETORIA															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	08				58	18	08		06	08			19	18	08	
PRETORIA	09																
PRETORIA	06	06				58	02	06		08	06			19	18	08	06
BRAAMFONTEIN	16	19	16			29	16			08	18	16		58	18	16	
BRAAMFONTEIN	18	08	18			58	18			06	08	18		29	28	18	
BRAAMFONTEIN	19	19				29	16	19		06	18	19		06	08	18	19
CAPE TOWN	28	29	28			58	48	28		08	06	28		06	28		
CAPE TOWN	29	29				19	16	29		58	48	28	29	06	28	29	
DURBAN	38	08	38			58	38			19	18	38		06	08	38	
DURBAN	39	08	38	39		58	38	39		19	18	38	39	06	03	39	
PORT ELIZABETH	48	58	48			08	18	58	48	29	28	48		06	02	58	48
BLOEMFONTEIN	58	58				08	18	58		19	18	58		06	02	58	
EAST LONDON	41	58	41			08	18	58	41	06	02	58	41	29	28	48	41
KLERKSDORP	02	06	02			08	06	02		58	02			29	28	06	02
WITBANK	03	06	03			08	06	03		58	08	06	03	29	28	06	03
RANDBURG	68	19	68			29	16	68		08	18	16	68	58	18	16	68
ROSEBANK	11	19	11			29	16	11		08	18	19	11	06	08	18	19

MINIMUM ESTIMATED TIME DELAY PATHS

DESTINATION		ROUTING FROM SYSTEM 09 IN PRETORIA															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	08				58	18	08		19	18	08		06	08		
PRETORIA	09																
PRETORIA	06	06				58	02	06		08	06			19	18	08	06
BRAAMFONTEIN	16	19	16			08	18	16		29	16			58	18	16	
BRAAMFONTEIN	18	08	18			58	18			19	18			06	08	18	
BRAAMFONTEIN	19	19				08	18	19		29	16	19		58	18	19	
CAPE TOWN	28	29	28			08	06	28		58	48	28		06	28		
CAPE TOWN	29	29				19	16	29		06	28	29		58	48	28	29
DURBAN	38	08	38			58	38			19	18	38		06	08	38	
DURBAN	39	08	38	39		58	38	39		06	03	39		19	18	38	39
PORT ELIZABETH	48	58	48			29	28	48		06	02	58	48	19	18	58	48
BLOEMFONTEIN	58	58				08	18	58		06	02	58		29	28	48	58
EAST LONDON	41	58	41			29	28	48	41	06	02	58	41	19	18	58	41
KLERKSDORP	02	06	02			08	06	02		58	02			29	28	06	02
WITBANK	03	06	03			08	06	03		29	28	06	03	58	02	06	03
RANDBURG	68	19	68			29	16	68		58	18	16	68	08	18	16	68
ROSEBANK	11	19	11			29	16	11		58	18	19	11	06	08	18	19

PATHS WITH THE LOWEST UTILIZED PRIMARY HOPS

DESTINATION		ROUTING FROM SYSTEM 09 IN PRETORIA															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	08				29	28	06	08	19	18	08		06	08		
PRETORIA	09																
PRETORIA	06	06				19	18	08	06	58	02	06		08	06		
BRAAMFONTEIN	16	19	16			08	18	16		29	16			58	18	16	
BRAAMFONTEIN	18	19	18			08	18			58	18			29	28	18	
BRAAMFONTEIN	19	19				06	18	19		29	16	19		58	18	19	
CAPE TOWN	28	29	28			08	06	28		58	48	28		19	18	28	
CAPE TOWN	29	29				19	16	29		58	48	28	29	06	28	29	
DURBAN	38	08	38			19	18	38		58	38			29	28	18	38
DURBAN	39	08	38	39		19	18	38	39	58	38	39		06	03	39	
PORT ELIZABETH	48	58	48			08	18	58	48	29	28	48		19	18	58	48
BLOEMFONTEIN	58	58				19	18	58		06	02	58		08	18	58	
EAST LONDON	41	58	41			08	18	58	41	19	18	58	41	06	02	58	41
KLERKSDORP	02	06	02			58	02			19	18	58	02	29	28	06	02
WITBANK	03	06	03			58	02	06	03	08	06	03		29	28	06	03
RANDBURG	68	19	68			58	18	16	68	29	16	68		08	18	16	68
ROSEBANK	11	19	11			58	18	19	11	29	16	11		08	18	19	11

SHORTEST PATHS

DESTINATION		ROUTING FROM SYSTEM 09 IN PRETORIA															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	08				06	08			19	18	08		58	18	08	
PRETORIA	09																
PRETORIA	06	06				08	06			19	18	08	06	58	02	06	
BRAAMFONTEIN	16	19	16			08	18	16		06	08	18	16	58	18	16	
BRAAMFONTEIN	18	08	18			19	18			06	08	18		58	18		
BRAAMFONTEIN	19	19				08	18	19		06	08	18	19	58	18	19	
CAPE TOWN	28	29	28			06	28			08	06	28		19	18	28	
CAPE TOWN	29	29				19	16	29		06	28	29		08	06	28	29
DURBAN	38	08	38			58	38			06	08	38		19	18	38	
DURBAN	39	08	38	39		06	03	39		58	38	39		19	18	38	39
PORT ELIZABETH	48	58	48			08	18	58	48	19	18	58	48	06	02	58	48
BLOEMFONTEIN	58	58				19	18	58		08	18	58		06	02	58	
EAST LONDON	41	58	41			08	18	58	41	19	18	58	41	06	02	58	41
KLERKSDORP	02	06	02			58	02			08	06	02		19	18	58	02
WITBANK	03	06	03			08	06	03		19	18	08	06	58	02	06	03
RANDBURG	68	19	68			08	18	16	68	06	08	18	16	58	18	16	68
ROSEBANK	11	19	11			08	18	19	11	06	08	18	19	58	18	19	11

MAXIMUM BANDWITH PATHS

DESTINATION		ROUTING FROM SYSTEM 06 IN PRETORIA																					
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE									
PRETORIA	08	08				03	39	38	08			28	18	08			02	58	08	08			
PRETORIA	09	09				02	58	08				28	29	09			08	09					
PRETORIA	06																21						
BRAAMFONTEIN	16	08	18	16		02	58	18	16			03	39	38	18	16		28	29	16			
BRAAMFONTEIN	18	08	18			02	58	18				28	18				03	39	38	18			
BRAAMFONTEIN	19	09	19			08	18	19				02	58	18	19			03	39	38	18	19	
CAPE TOWN	28	28				02	58	48	28			03	39	38	18	28		08	18	28			
CAPE TOWN	29	09	29			28	29					02	58	48	28	29		03	39	38	18	28	29
DURBAN	38	08	38			02	58	38				28	18	38				03	39	38			
DURBAN	39	03	39			08	38	39				09	08	38	39			02	58	38	39		
PORT ELIZABETH	48	09	58	48		28	48					02	58	48				08	18	58	48		
BLOEMFONTEIN	58	09	58			02	58					28	48	58				03	39	38	58		
EAST LONDON	41	09	58	41		28	58	41				28	48	41				08	18	58	41		
KLERKSDORP	02	02				03	39	38	58	02		09	58	02				08	09	58	02		
WITBANK	03	03				02	58	38	39	03		08	38	39	03			09	08	38	39	03	
RANDBURG	68	09	19	68		02	58	18	16	68		03	39	38	18	16	68	08	18	16	68		
ROSEBANK	11	09	19	11		08	18	19	11			02	58	18	19	11		03	39	38	18	19	11

MINIMUM ESTIMATED TIME DELAY PATHS

DESTINATION		ROUTING FROM SYSTEM 06 IN PRETORIA																		
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE						
PRETORIA	08	08				03	39	38	08		09	08			02	58	09	08		
PRETORIA	09	09				02	58	09			08	09			28	29	09			
PRETORIA	06																			
BRAAMFONTEIN	16	09	19	16		08	18	16			28	29	16		02	58	18	16		
BRAAMFONTEIN	18	08	18			02	58	18			28	18			03	39	38	18		
BRAAMFONTEIN	19	09	19			03	39	38	18	19	08	18	19		28	18	19			
CAPE TOWN	28	28				08	18	28			03	39	38	18	28	02	58	48	28	
CAPE TOWN	29	09	29			28	29				08	09	29		03	39	38	18	28	29
DURBAN	38	08	38			02	58	38			03	39	38		28	18	38			
DURBAN	39	03	39			02	58	38	39		08	38	39		28	18	38	39		
PORT ELIZABETH	48	09	58	48		28	48				02	58	48		03	39	38	58	48	
BLOEMFONTEIN	58	09	58			02	58				03	39	38	58	08	09	58			
EAST LONDON	41	09	58	41		28	48	41			02	58	41		08	18	58	41		
KLERKSDORP	02	02				03	39	38	58	02	09	58	02		28	48	58	02		
WITBANK	03	03				02	58	38	39	03	08	38	39	03	09	08	38	39	03	
RANDBURG	68	09	19	68		02	58	18	16	68	08	18	16	68	03	39	38	18	16	68
ROSEBANK	11	09	19	11		02	58	18	19	11	08	18	19	11	28	18	19	11		

PATHS WITH THE LOWEST UTILIZED PRIMARY HOPS

DESTINATION		ROUTING FROM SYSTEM 06 IN PRETORIA																					
DSE (NODE)	SYSTEM	1 st ROUTE					2 nd ROUTE					3 rd ROUTE					4 th ROUTE						
PRETORIA	08	08					03	39	38	08			28	18	08			02	58	09	08		
PRETORIA	09	09					02	58	09				28	29	09			08	09				
PRETORIA	06																						
BRAAMFONTEIN	16	08	18	16			02	58	18	16			28	29	16			03	39	38	18	16	
BRAAMFONTEIN	18	08	18				28	18					03	39	38	18		02	58	18			
BRAAMFONTEIN	19	09	19				02	58	18	19			03	39	38	18	19	08	18	19			
CAPE TOWN	28	28					02	58	48	28			03	39	38	18	28	08	18	28			
CAPE TOWN	29	09	29				03	39	38	18	28	29	28	29				08	09	29			
DURBAN	38	08	38				02	58	38				28	18	38			03	39	38			
DURBAN	39	03	39				02	58	38	39			28	18	38	39		08	38	39			
PORT ELIZABETH	48	09	58	48			28	48					03	39	38	58	48	02	58	48			
BLOEMFONTEIN	58	09	58				02	58					03	39	38	58		28	48	58			
EAST LONDON	41	09	58	41			03	39	38	58	41		28	48	41			08	18	58	41		
KLERKSDORP	02	02					03	39	38	58	02		28	48	58	02		08	09	58	02		
WITBANK	03	03					02	58	38	39	03		08	38	39	03		09	08	38	39	03	
RANDBURG	68	09	19	68			02	58	18	16	68		28	18	16	68		08	18	16	68		
ROSEBANK	11	09	19	11			02	58	18	19	11		28	18	19	11		08	18	19	11		

SHORTEST PATHS

DESTINATION		ROUTING FROM SYSTEM 06 IN PRETORIA																										
DSE (NODE)	SYSTEM	1 st ROUTE					2 nd ROUTE					3 rd ROUTE					4 th ROUTE											
PRETORIA	08	08					09	08					02	58	09	08					03	39	38	08				
PRETORIA	09	09					08	09					02	58	09						03	39	38	08	09			
PRETORIA	06																											
BRAAMFONTEIN	16	09	19	16			08	18	16				02	58	38	18	16				03	39	38	18	16			
BRAAMFONTEIN	18	08	18				09	08	18				02	58	18						03	39	38	18				
BRAAMFONTEIN	19	09	19				08	18	19				02	58	18	19					03	39	38	18	19			
CAPE TOWN	28	28					09	29	28				08	18	28						02	58	48	28				
CAPE TOWN	29	09	29				28	29					08	09	29						02	58	48	28	29			
DURBAN	38	08	38				09	08	38				03	39	38						02	58	38					
DURBAN	39	03	39				09	38	39				02	58	38	39					28	18	38	39				
PORT ELIZABETH	48	09	58	48			02	58	48				06	18	58	48					28	48						
BLOEMFONTEIN	58	09	58				02	58					08	09	58						03	39	38	58				
EAST LONDON	41	09	58	41			09	58	41				02	58	41						08	18	58	41				
KLERKSDORP	02	02					09	58	02				08	09	58	02					03	39	36	58	02			
WITBANK	03	03					08	38	39	03			09	08	38	39	03				02	58	38	39	03			
RANDBURG	68	09	19	68			08	18	16	68			02	58	18	16	68				03	39	38	18	16	68		
ROSEBANK	11	09	19	11			08	18	19	11			02	58	18	19	11				03	39	38	18	19	11		

MAXIMUM BANDWIDTH PATHS

DESTINATION -		ROUTING FROM SYSTEM 16 IN BRAAMFONTEIN																					
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE									
PRETORIA	08	18	08				68	19	09	08			29	09	08			19	18	08			
PRETORIA	09	19	09				29	09					11	19	09			68	19	09			
PRETORIA	06	18	08	06			29	28	06				19	09	06			11	19	09	06		
BRAAMFONTEIN	15																						
BRAAMFONTEIN	18	18					19	18					11	19	18			68	19	18			
BRAAMFONTEIN	19	19					11	19					68	19				29	09	19			
CAPE TOWN	28	29	28				18	28					19	18	28			11	19	18	28		
CAPE TOWN	29	29					11	19	09	29			68	19	09	29			19	09	29		
DURBAN	38	18	38				19	18	38				11	19	18	38			68	19	18	38	
DURBAN	39	18	38	39			19	18	38	39			11	19	18	38	39		68	19	18	38	39
PORT ELIZABETH	48	18	58	48			29	28	48				19	18	58	48			11	19	18	58	48
BLOEMFONTEIN	58	18	58				19	18	58				11	19	18	58			68	19	18	58	
EAST LONDON	41	18	58	41			19	18	58	41			11	19	18	58	41		68	19	18	58	41
KLERKSDORP	02	18	58	02			19	09	06	02			11	19	09	06	02		68	19	09	06	02
WITBANK	03	18	06	06	03		29	28	06	03			19	09	06	03			11	19	09	06	03
RANOBURG	68	68					11	19	68				29	09	19	68			19	68			
ROSEBANK	11	11					68	19	11				29	09	19	11			19	11			

MINIMUM ESTIMATED TIME DELAY PATHS

DESTINATION		ROUTING FROM SYSTEM 16 IN BRAAMFONTEIN																				
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE								
PRETORIA	08	18	08			29	09	08			68	19	09	08			11	19	18	08		
PRETORIA	09	19	09			29	09				68	19	09				11	19	09			
PRETORIA	06	18	08	06		29	28	06			19	09	06				11	19	09	06		
BRAAMFONTEIN	16																					
BRAAMFONTEIN	18	18				11	19	18			68	19	18				19	18				
BRAAMFONTEIN	19	19				11	19				68	19					29	09	19			
CAPE TOWN	28	29	28			18	28				19	18	28				68	19	18	28		
CAPE TOWN	29	29				18	28	29			19	09	29				11	19	02	29		
DURBAN	38	18	38			68	19	18	38		11	19	18	38			19	18	38			
DURBAN	39	18	38	39		68	19	18	38	39	11	19	18	38	39		19	18	38	39		
PORT ELIZABETH	48	18	58	48		29	28	48			19	18	58	48			68	19	18	58	48	
BLOEMFONTEIN	58	18	58			68	19	18	58		11	19	18	58			19	18	58			
EAST LONDON	41	18	58	41		29	28	58	41		11	19	18	58	41		19	18	58	41		
KLERKSDORP	02	18	58	02		29	09	06	02		11	19	09	06	02		19	09	06	02		
WITBANK	03	18	06	06	03		29	28	06	03		11	19	09	06	03		68	19	09	06	03
HANDBURG	68	68				11	19	68			19	68					18	19	68			
ROSEBANK	11	11				68	19	11			19	11					18	19	11			

PATHS WITH THE LOWEST UTILIZED PRIMARY HOPS

DESTINATION		ROUTING FROM SYSTEM 16 IN BRAAMFONTEIN																			
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE							
PRETORIA	08	18	08			29	09	08			19	18	08			68	19	09	08		
PRETORIA	09	19	09			68	19	09			29	09				11	19	09			
PRETORIA	06	18	08	06		68	19	09	06		11	19	09	06		29	28	06			
BRAAMFONTEIN	16																				
BRAAMFONTEIN	18	18				11	19	18			68	19	18			29	28	18			
BRAAMFONTEIN	19	19				11	19				68	19				29	09	19			
CAPE TOWN	28	29	28			68	19	18	28		19	18	28			11	19	18	28		
CAPE TOWN	29	29				11	19	09	29		68	19	09	29		18	28	29			
DURBAN	38	18	38			11	19	18	38		68	19	18	38		29	28	18	38		
DURBAN	39	18	38	39		11	19	18	38	39	68	19	18	38	39	19	18	38	39		
PORT ELIZABETH	48	18	58	48		68	19	18	58	48	29	28	48			19	18	58	48		
BLOEMFONTEIN	58	18	58			68	19	18	58		11	19	18	58		29	28	48	58		
EAST LONDON	41	18	58	41		68	19	18	58	41	29	28	58	41		19	18	58	41		
KLERKSDORP	02	18	58	02		68	19	09	06	02	11	19	09	06	02	29	09	06	02		
WITBANK	03	18	08	06	03	29	28	06	03		19	09	06	03		11	19	09	06	03	
RANOBURG	68					11	19	68			29	09	19	68		19	68				
ROSEBANK	11	11				68	19	11			29	09	19	11		19	11				

SHORTEST PATHS

DESTINATION		ROUTING FROM SYSTEM 16 IN BRAAMFONTEIN																					
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE									
PRETORIA	08	18	08				19	18	08				11	19	18	08		68	19	09	08		
PRETORIA	09	19	09				18	19	09				11	19	09			68	19	09			
PRETORIA	06	19	09	06			18	11	06				11	19	09	06		68	19	09	06		
BRAAMFONTEIN	16																						
BRAAMFONTEIN	18	18					19	18					11	19	18			68	19	18			
BRAAMFONTEIN	19	19					18	19					11	19				68	19				
CAPE TOWN	28	29	28				18	28					19	18	28			11	19	18	28		
CAPE TOWN	29	29					18	28	29				19	09	29			11	19	09	29		
DURBAN	38	18	38				19	18	38				11	19	18	38		68	19	18	38		
DURBAN	39	18	38	39			19	18	38	39			11	19	18	38	39	68	19	18	38	39	
PORT ELIZABETH	48	11	58	48			19	18	58	48			29	28	48			11	19	18	58	48	
BLOEMFONTEIN	58	18	58				19	18	58				11	19	18	58		68	19	18	58		
EAST LONDON	41	18	58	41			19	18	58	41			11	19	18	58	41	68	19	18	58	41	
KLERKSDORP	02	18	58	02			19	09	06	02			11	19	09	06	02	68	19	09	06	02	
WITBANK	03	19	09	06	03		18	06	06	03			11	19	09	06	03	68	19	09	06	03	
RANDBURG	68	68					19	68					18	19	68			11	19	68			
ROSEBANK	11	11					19	11					18	19	11			68	19	11			

MAXIMUM BANDWIDTH PATHS

DESTINATION		ROUTING FROM SYSTEM 18 IN BRAAMFONTEIN																
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE				
PRETORIA	08	08				38	08			58	09	08		28	06	08		
PRETORIA	09	19	09			58	09			28	29	09		08	09			
PRETORIA	06	08	06			28	06			38	08	06		19	09	06		
BRAAMFONTEIN	16	16				58	09	19	16	19	16			28	29	16		
BRAAMFONTEIN	18																	
BRAAMFONTEIN	19	19				58	09	19		16	19			06	09	19		
CAPE TOWN	28	28				38	58	48	28	58	48	28		08	06	28		
CAPE TOWN	29	28	29			16	29			19	16	29		58	48	28	29	
DURBAN	38	38				08	38			58	38			19	09	08	38	
DURBAN	39	38	39			28	06	03	39	08	38	39		58	38	39		
PORT ELIZABETH	48	58	48			28	48			38	58	48		16	19	09	58	48
BLOEMFONTEIN	58	58				38	58			19	09	58		16	19	09	58	
EAST LONDON	41	58	41			28	58	41		19	09	58	41	38	58	41		
KLERKSDORP	02	58	02			28	06	02		08	06	02		38	58	02		
WITSBANK	03	08	06	03		28	06	03		38	39	03		19	09	06	03	
RANDBURG	68	16	68			50	09	19	68	19	68			08	09	19	68	
ROSEBANK	11	19	11			16	11			28	29	16	11	58	09	19	11	

MINIMUM ESTIMATED TIME DELAY PATHS

DESTINATION		ROUTING FROM SYSTEM 18 IN BRAAMFONTEIN															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	08				38	08			28	06	08		19	09	08	
PRETORIA	09	19	09			58	09			08	09			28	29	09	
PRETORIA	06	08	06			28	06			38	08	06		58	09	06	
BRAAMFONTEIN	16	16				19	16			28	29	16		58	09	19	16
BRAAMFONTEIN	18																
BRAAMFONTEIN	19	19				16	19			58	09	19		08	09	19	
CAPE TOWN	28	28				08	06	28		58	48	28		16	29	28	
CAPE TOWN	29	28	29			16	29			19	16	29		38	08	09	29
DURBAN	38	38				08	38			58	38			19	09	08	38
DURBAN	39	38	39			28	06	03	39	08	38	39		58	38	39	
PORT ELIZABETH	48	58	48			28	48			38	58	48		19	09	58	48
BLOEMFONTEIN	58	58				38	58			19	09	58		08	09	58	
EAST LONDON	41	58	41			28	58	41		19	09	58	41	38	58	41	
KLERKSDORP	02	58	02			28	06	02		08	06	02		38	58	02	
WITSBANK	03	08	06	03		28	06	03		38	39	03		58	09	06	03
RANDBURG	68	16	68			19	68			08	09	19	68	58	09	19	68
ROSEBANK	11	19	11			16	11			58	09	19	11	28	29	16	11

PATHS WITH THE LOWEST UTILIZED PRIMARY HOPS

DESTINATION		ROUTING FROM SYSTEM 18 IN BRAAMFONTEIN																
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE				
PRETORIA	08	08				28	06	08		38	08			58	09	08		
PRETORIA	09	08	09			38	08	09		16	19	09		58	09			
PRETORIA	06	08	06			38	08	06		19	09	06		16	19	09	06	
BRAAMFONTEIN	16	16				28	29	16		38	08	09	19	06	09	19	16	
BRAAMFONTEIN	18																	
BRAAMFONTEIN	19	19				28	29	16	19	38	08	09	19	06	09	19		
CAPE TOWN	28	28				38	58	48	28	16	29	28		08	06	28		
CAPE TOWN	29	28	29			58	08	09	29	19	16	29		16	29			
DURBAN	38	38				28	48	58	38	08	38			58	38			
DURBAN	39	38	39			08	38	39		28	06	03	39	19	09	08	38	39
PORT ELIZABETH	48	58	48			38	58	48		28	48			19	09	58	48	
BLOEMFONTEIN	58	58				28	48	58		08	09	58		16	19	09	58	
EAST LONDON	41	58	41			38	58	41		16	19	09	58	08	09	58	41	
KLERKSDORP	02	58	02			28	06	02		08	06	02		19	09	06	02	
WITSBANK	03	08	06	03		38	39	03		16	19	09	06	03	19	09	06	03
RANDBURG	68	16	68			38	08	09	19	08	09	19	68	19	68			
ROSEBANK	11	19	11			38	08	09	19	28	29	16	11	16	11			

SHORTEST PATHS

DESTINATION		ROUTING FROM SYSTEM 18 IN BRAAMFONTEIN																	
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE					
PRETORIA	08	08				19	09	08			38	08			16	19	09	08	
PRETORIA	09	08	09			19	09				16	19	09		58	09			
PRETORIA	06	08	06			19	09	06			16	19	09	06		58	09	06	
BRAAMFONTEIN	16	16				19	16				08	09	19	16		58	09	19	16
BRAAMFONTEIN	18																		
BRAAMFONTEIN	19	19				16	19				08	09	19		08	09	19		
CAPE TOWN	28	28				16	29	28			08	06	28		58	48	28		
CAPE TOWN	29	28	29			16	29				19	16	29		08	09	29		
DURBAN	38	38				08	38				58	38			19	09	08	38	
DURBAN	39	38	39			08	38	39			58	38	39		19	09	08	38	39
PORT ELIZABETH	48	58	48			28	48				38	58	48		08	09	58	48	
BLOEMFONTEIN	58	58				08	09	58			19	09	58		38	58			
EAST LONDON	41	58	41			08	09	58	41		19	09	58	41		38	58	41	
KLERKSDORP	02	58	02			08	09	02			19	09	06	02		38	58	02	
WITSBANK	03	08	06	03		19	09	06	03		38	39	03		16	19	09	06	03
RANDBURG	68	16	68			19	68				08	09	19	68		58	09	19	68
ROSEBANK	11	19	11			16	11				08	09	19	11		58	09	19	11

MAXIMUM BANDWIDTH PATHS

DESTINATION		ROUTING FROM SYSTEM 19 IN BRAAMFONTEIN															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	09	08			16	18	08		16	18	08		11	16	18	08
PRETORIA	09	09				16	18	08	09	11	16	18	08	09			
PRETORIA	06	09	06			16	18	08	06	11	16	18	08	06			
BRAAMFONTEIN	16	16				11	16			68	16			09	08	18	16
BRAAMFONTEIN	18	18				16	18			11	16	18		68	16	18	
BRAAMFONTEIN	19																
CAPE TOWN	28	16	28			16	29	28		09	29	28		11	16	29	28
CAPE TOWN	29	16	29			68	16	29		11	16	29		09	29		
DURBAN	38	18	38			16	18	38		11	16	18	38		09	08	38
DURBAN	39	18	38	39		16	18	38	39	09	08	38	39	11	16	18	38
PORT ELIZABETH	48	18	58	48		09	58	48		16	18	58	48	11	16	18	58
BLOEMFONTEIN	58	18	58			09	58			16	18	58		11	16	18	58
EAST LONDON	41	18	58	41		09	58	41		16	18	58	41	11	16	18	58
KLERKSDORP	02	09	06	02		16	58	02		16	18	58	02	11	16	18	58
MITBANK	03	08	06	03		18	08	06	03	16	18	08	06	11	16	18	08
RANDBURG	68	68				11	16	68		16	68			09	08	18	16
ROSEBANK	11	11				68	16	11		16	11			09	08	18	16

MINIMUM ESTIMATED TIME DELAY PATHS

DESTINATION		ROUTING FROM SYSTEM 19 IN BRAAMFONTEIN															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	09	08			68	16	18	08	11	16	18	08	16	18	08	
PRETORIA	09	09				16	18	08	09	68	16	18	08	11	16	18	08
PRETORIA	06	09	06			18	08	06		11	16	18	08	68	16	18	08
BRAAMFONTEIN	16	16				68	16			11	16			18	16		
BRAAMFONTEIN	18	18				16	18			11	16	18		68	16	18	
BRAAMFONTEIN	19																
CAPE TOWN	28	18	28			68	16	29	28	11	16	29	28	16	29	28	
CAPE TOWN	29	16	29			11	16	29		68	16	29		09	29		
DURBAN	38	18	38			11	16	18	38	68	16	18	38	16	18	38	
DURBAN	39	18	38	39		68	16	18	38	11	16	18	38	16	18	38	39
PORT ELIZABETH	48	18	58	48		09	58	48		16	18	58	48	68	16	18	58
BLOEMFONTEIN	58	18	58			09	58			68	16	18	58	16	18	58	
EAST LONDON	41	18	58	41		09	58	41		68	16	18	58	16	18	58	41
KLERKSDORP	02	09	06	02		11	16	18	58	68	16	18	58	16	18	58	02
MITBANK	03	08	06	03		11	16	18	08	68	16	18	08	68	16	18	08
RANDBURG	68	68				11	16	68		16	68			18	16	68	
ROSEBANK	11	11				68	16	11		16	11			18	16	11	

PATHS WITH THE LOWEST UTILIZED PRIMARY HOPS

DESTINATION		ROUTING FROM SYSTEM 19 IN BRAAMFONTEIN															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	09	08			11	16	18	08	16	18	08		68	16	18	08
PRETORIA	09	09				16	18	08	09	11	16	18	08	09			
PRETORIA	06	09	06			68	16	18	08	11	16	18	08	06			
BRAAMFONTEIN	16	16				68	16			11	16			09	08	18	16
BRAAMFONTEIN	18	18				11	16	18		16	18			68	16	18	
BRAAMFONTEIN	19																
CAPE TOWN	28	18	28			11	16	29	28	16	29	28		68	16	29	28
CAPE TOWN	29	16	29			68	16	29		11	16	29		09	29		
DURBAN	38	18	38			16	18	38		11	16	18	38	68	16	18	38
DURBAN	39	18	38	39		11	16	18	38	16	18	38	39	68	16	18	38
PORT ELIZABETH	48	18	58	48		68	18	18	58	11	16	18	58	09	58	48	
BLOEMFONTEIN	58	18	58			16	18	58		11	16	18	58	09	58		
EAST LONDON	41	18	58	41		16	18	58	41	11	16	18	58	09	58	41	
KLERKSDORP	02	09	06	02		11	16	18	58	68	16	18	58	02			
MITBANK	03	08	06	03		16	18	08	06	11	16	18	08	06	03		
RANDBURG	68	68				11	16	68		16	68			09	08	18	16
ROSEBANK	11	11				68	16	11		16	11			09	08	18	16

SHORTEST PATHS

DESTINATION		ROUTING FROM SYSTEM 19 IN BRAAMFONTEIN															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	09	08			18	08			16	18	08		11	16	18	08
PRETORIA	09	09				18	08	09		16	18	08	09	11	16	18	08
PRETORIA	06	09	06			18	08	06		16	18	08	06	11	16	18	08
BRAAMFONTEIN	16	16				18	16			11	16			68	16		
BRAAMFONTEIN	18	18				16	18			11	16	18		68	16	18	
BRAAMFONTEIN	19																
CAPE TOWN	28	18	28			16	29	28		09	29	28		11	16	29	28
CAPE TOWN	29	16	29			09	29			18	28	29		11	16	29	
DURBAN	38	18	38			16	18	38		09	08	38		11	16	18	38
DURBAN	39	18	38	39		16	18	38	39	09	08	38	39	11	16	18	38
PORT ELIZABETH	48	18	58	48		09	58	48		16	18	58	48	11	16	18	58
BLOEMFONTEIN	58	18	58			09	58			16	18	58		11	16	18	58
EAST LONDON	41	18	58	41		09	58	41		16	18	58	41	11	16	18	58
KLERKSDORP	02	09	06	02		18	58	02		16	18	58	02	11	16	18	58
MITBANK	03	08	06	03		18	08	06	03	16	18	08	06	11	16	18	08
RANDBURG	68	68				16	68			18	16	68		11	16	68	
ROSEBANK	11	11				16	11			18	16	11		68	16	11	

MAXIMUM BANDWIDTH PATHS

DESTINATION		ROUTING FROM SYSTEM 28 IN CAPE TOWN															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	06	08			18	08			48	58	18	08	29	09	08	
PRETORIA	09	29	09			48	58	09		06	09			18	19	09	
PRETORIA	06	06				18	08	06		29	09	06		48	58	09	06
BRAAMFONTEIN	16	29	16			18	16			06	08	18	16	48	58	18	16
BRAAMFONTEIN	18	18				06	08	18		29	16	18		48	58	18	
BRAAMFONTEIN	19	18	19			29	16	19		48	58	18	19	06	09	19	
CAPE TOWN	28																
CAPE TOWN	29	29				18	16	29		06	09	29		48	58	09	29
DURBAN	38	18	38			48	58	38		29	16	18	38	06	08	38	
DURBAN	39	18	38	39		06	03	39		48	58	38	39	29	16	18	38
PORT ELIZABETH	48	48				18	58	48		29	09	58	48	06	09	58	48
BLOEMFONTEIN	58	48	58			18	58			29	09	58		06	09	58	
EAST LONDON	41	48	41			29	09	58	41	18	58	41		06	09	58	41
KLERKSDORP	02	06	02			18	58	02		48	58	02		29	09	06	02
WITBANK	03	06	03			18	08	06	03	29	09	06	03	48	58	09	06
RANDBURG	68	18	16	68		48	58	18	16	29	16	68		06	09	19	68
ROSEBANK	11	18	19	11		06	09	19	11	48	58	18	19	29	16	11	

MINIMUM ESTIMATED TIME DELAY PATHS

DESTINATION		ROUTING FROM SYSTEM 28 IN CAPE TOWN															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	06	08			18	08			29	09	08		48	58	18	08
PRETORIA	09	29	09			06	09			48	58	09		18	19	09	
PRETORIA	06	06				18	08	06		29	09	06		48	58	09	06
BRAAMFONTEIN	16	29	16			18	16			06	08	18	16	48	58	18	16
BRAAMFONTEIN	18	18				06	08	18		48	58	18		29	16	18	
BRAAMFONTEIN	19	18	19			29	16	19		06	09	19		48	58	18	19
CAPE TOWN	28																
CAPE TOWN	29	29				18	16	29		06	09	29		48	58	09	29
DURBAN	38	18	38			48	58	38		29	16	18	38	06	08	38	
DURBAN	39	18	38	39		06	03	39		48	58	38	39	29	16	18	38
PORT ELIZABETH	48	48				18	58	48		29	09	58	48	06	09	58	48
BLOEMFONTEIN	58	48	58			29	09	58		18	58			06	09	58	
EAST LONDON	41	48	41			06	09	58	41	29	09	58	41	18	58	41	
KLERKSDORP	02	06	02			48	58	02		18	58	02		29	09	06	02
WITBANK	03	06	03			18	08	06	03	29	09	06	03	48	58	09	06
RANDBURG	68	18	16	68		48	58	18	16	29	16	68		06	09	19	68
ROSEBANK	11	18	19	11		06	09	19	11	48	58	18	19	29	16	11	

PATHS WITH THE LOWEST UTILIZED PRIMARY HOPS

DESTINATION		ROUTING FROM SYSTEM 28 IN CAPE TOWN															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	06	08			48	58	18	08	29	09	08		18	08		
PRETORIA	09	29	09			48	58	09		06	09			18	19	09	
PRETORIA	06	06				48	58	09	06	18	08	06		29	09	06	
BRAAMFONTEIN	16	29	16			48	58	18	16	19	16			06	08	18	16
BRAAMFONTEIN	18	18				06	08	18		29	16	18		48	58	18	
BRAAMFONTEIN	19	18	19			48	58	18	19	29	16	19		06	09	19	
CAPE TOWN	28																
CAPE TOWN	29	29				06	09	29		18	16	29		48	58	09	29
DURBAN	38	18	38			48	58	38		29	16	18	38	06	08	38	
DURBAN	39	18	38	39		06	03	39		48	58	38	39	29	16	18	38
PORT ELIZABETH	48	48				06	09	58	48	29	09	58	48	18	58	48	
BLOEMFONTEIN	58	48	58			29	09	58		18	58			06	09	58	
EAST LONDON	41	48	41			06	09	58	41	29	09	58	41	18	58	41	
KLERKSDORP	02	06	02			48	58	02		29	09	06	02	18	58	02	
WITBANK	03	06	03			29	09	06	03	18	08	06	03	48	58	09	06
RANDBURG	68	18	16	68		06	09	18	68	48	58	18	16	29	16	68	
ROSEBANK	11	18	19	11		06	09	19	11	48	58	18	19	29	16	11	

SHORTEST PATHS

DESTINATION		ROUTING FROM SYSTEM 28 IN CAPE TOWN															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	06	08			18	08			29	09	08		48	58	18	08
PRETORIA	09	29	09			06	09			18	19	09		48	58	09	
PRETORIA	06	06				29	09	06		18	08	06		48	58	09	06
BRAAMFONTEIN	16	29	16			18	16			06	08	18	16	48	58	18	16
BRAAMFONTEIN	18	18				29	16	18		06	08	18		48	58	18	
BRAAMFONTEIN	19	18	19			29	16	19		06	09	19		48	58	18	19
CAPE TOWN	28																
CAPE TOWN	29	29				18	16	29		06	09	29		48	58	09	29
DURBAN	38	18	38			48	58	38		06	08	38		29	16	18	38
DURBAN	39	18	38	39		06	03	39		48	58	38	39	29	16	18	38
PORT ELIZABETH	48	48				18	58	48		29	09	58	48	06	09	58	48
BLOEMFONTEIN	58	48	58			29	09	58		18	58			06	09	58	
EAST LONDON	41	48	41			06	09	58	41	29	09	58	41	18	58	41	
KLERKSDORP	02	06	02			48	58	02		18	58	02		29	09	06	02
WITBANK	03	06	03			29	09	06	03	18	08	06	03	48	58	09	06
RANDBURG	68	18	16	68		06	09	18	68	48	58	18	16	29	16	68	
ROSEBANK	11	18	19	11		06	09	19	11	48	58	18	19	29	16	11	

MAXIMUM BANDWITH PATHS

DESTINATION		ROUTING FROM SYSTEM 29 IN CAPE TOWN															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	09	08			16	18	08		28	06	08					
PRETORIA	09	09				16	19	09		28	06	09					
PRETORIA	06	09	06			28	06			16	19	09	06				
BRAAMFONTEIN	16	16				09	19	16		28	18	16					
BRAAMFONTEIN	18	28	18			09	08	18		16	18						
BRAAMFONTEIN	19	16	19			09	19			28	18	19					
CAPE TOWN	28	28				16	18	28		09	06	28					
CAPE TOWN	29																
DURBAN	38	16	18	38		09	08	38		28	18	38					
DURBAN	39	16	18	38	39		09	08	38	39		28	18	38	39		
PORT ELIZABETH	48	28	48			09	58	48		16	18	58	48				
BLOEMFONTEIN	58	28	48	58		09	58			16	18	58					
EAST LONDON	41	28	48	41		09	58	41		16	18	58	41				
KLERKSDORP	02	09	06	02		16	18	58	02	28	06	02					
WITSBANK	03	09	06	03		28	06	03		16	19	09	06	03			
RANDBURG	68	16	68			09	19	68		28	18	19	68				
ROSEBANK	11	16	11			09	19	11		28	18	19	11				

MINIMUM ESTIMATED TIME DELAY PATHS

DESTINATION		ROUTING FROM SYSTEM 29 IN CAPE TOWN															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	09	08			16	18	08		28	06	08					
PRETORIA	09	09				16	19	09		28	06	09					
PRETORIA	06	09	06			28	06			16	19	09	06				
BRAAMFONTEIN	16	16				09	19	16		28	18	16					
BRAAMFONTEIN	18	28	18			16	18			09	08	18					
BRAAMFONTEIN	19	16	19			09	19			28	18	19					
CAPE TOWN	28	28				16	18	28		09	06	28					
CAPE TOWN	29																
DURBAN	38	16	18	38		09	08	38		28	18	38					
DURBAN	39	16	18	38	39		09	08	38	39		28	18	38	39		
PORT ELIZABETH	48	28	48			09	58	48		16	18	58	48				
BLOEMFONTEIN	58	28	48	58		09	58			16	18	58					
EAST LONDON	41	28	48	41		09	58	41		16	18	58	41				
KLERKSDORP	02	09	06	02		28	06	02		16	18	58	02				
WITSBANK	03	09	06	03		28	06	03		16	19	09	06	03			
RANDBURG	68	16	68			09	19	68		28	18	19	68				
ROSEBANK	11	16	11			09	19	11		28	18	19	11				

PATHS WITH THE LOWEST UTILIZED PRIMARY HOPS

DESTINATION		ROUTING FROM SYSTEM 29 IN CAPE TOWN															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	09	08			16	18	08		28	06	08					
PRETORIA	09	09				16	19	09		28	06	09					
PRETORIA	06	09	06			16	19	09	06	28	06						
BRAAMFONTEIN	16	16				09	19	16		28	18	16					
BRAAMFONTEIN	18	28	18			09	08	18		16	18						
BRAAMFONTEIN	19	16	19			09	19			28	18	19					
CAPE TOWN	28	28				16	18	28		09	06	28					
CAPE TOWN	29																
DURBAN	38	16	18	38		09	08	38		28	18	38					
DURBAN	39	16	18	38	39		09	08	38	39		28	18	38	39		
PORT ELIZABETH	48	28	48			09	58	48		16	18	58	48				
BLOEMFONTEIN	58	28	48	58		09	58			16	18	58					
EAST LONDON	41	28	48	41		09	58	41		16	18	58	41				
KLERKSDORP	02	09	06	02		28	06	02		16	18	58	02				
WITSBANK	03	09	06	03		28	06	03		16	19	09	06	03			
RANDBURG	68	16	68			09	19	68		28	18	19	68				
ROSEBANK	11	16	11			09	19	11		28	18	19	11				

SHORTEST PATHS

DESTINATION		ROUTING FROM SYSTEM 29 IN CAPE TOWN															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	09	08			28	06	08		16	18	08					
PRETORIA	09	09				16	19	09		28	06	09					
PRETORIA	06	09	06			28	06			16	19	09	06				
BRAAMFONTEIN	16	16				28	18	16		09	19	16					
BRAAMFONTEIN	18	28	18			16	18			09	08	18					
BRAAMFONTEIN	19	16	19			09	19			28	18	19					
CAPE TOWN	28	28				16	18	28		09	06	28					
CAPE TOWN	29																
DURBAN	38	16	18	38		28	18	38		09	08	38					
DURBAN	39	28	18	38	39		16	18	38	39		09	08	38	39		
PORT ELIZABETH	48	28	48			09	58	48		16	18	58	48				
BLOEMFONTEIN	58	28	48	58		09	58			16	18	58					
EAST LONDON	41	28	48	41		09	58	41		16	18	58	41				
KLERKSDORP	02	09	06	02		28	06	02		16	18	58	02				
WITSBANK	03	09	06	03		28	06	03		16	19	09	06	03			
RANDBURG	68	16	68			09	19	68		28	18	19	68				
ROSEBANK	11	16	11			09	19	11		28	18	19	11				

MAXIMUM BANDWIDTH PATHS-

DESTINATION		ROUTING FROM SYSTEM 38 IN DURBAN															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	08				18	08			58	18	08		39	03	06	08
PRETORIA	09	08	09			58	09			39	03	06	09	18	19	09	
PRETORIA	06	08	06			39	03	06		18	08	06		58	09	06	
BRAAMFONTEIN	16	18	16			08	18	16		58	18	16		39	03	06	09 19 16
BRAAMFONTEIN	18	18				58	18			08	18			39	03	06	08 18
BRAAMFONTEIN	19	18	19			39	03	06	09 19	08	09	19		58	18	19	
CAPE TOWN	28	18	28			58	48	28		39	03	06	28	08	06	28	
CAPE TOWN	29	18	28	29		58	48	29		08	09	29		39	03	06	09 29
DURBAN	38																
DURBAN	39	39				08	06	03	39	18	08	06	03	58	09	06	03 39
PORT ELIZABETH	48	58	48			18	58	48		08	18	58	48	39	03	06	09 58 48
BLOEMFONTEIN	58	58				18	58			39	03	06	09 58	08	09	58	
EAST LONDON	41	58	41			18	58	41		08	18	58	41	39	03	06	09 58 41
KLERKSDORP	02	58	02			18	58	02		39	03	06	02	08	06	02	
WITBANK	03	39	03			08	06	03		18	08	06	03	58	09	06	03
RANDBURG	68	18	16	68		58	18	16	68	39	03	06	09 19 68	08	09	19	68
ROSEBANK	11	18	19	11		08	18	19	11	58	18	19	11	39	03	06	09 19 11

MINIMUM ESTIMATED TIME DELAY PATHS

DESTINATION		ROUTING FROM SYSTEM 38 IN DURBAN															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	08				18	08			39	03	06	08	58	18	08	
PRETORIA	09	08	09			58	09			39	03	06	09	18	19	09	
PRETORIA	06	08	06			39	03	06		18	08	06		58	09	06	
BRAAMFONTEIN	16	18	16			58	18	16		08	18	16		39	03	06	09 19 16
BRAAMFONTEIN	18	18				58	18			08	18			39	03	06	08 18
BRAAMFONTEIN	19	18	19			39	03	06	09 19	08	09	19		58	18	19	
CAPE TOWN	28	18	28			58	48	28		39	03	06	28	08	06	28	
CAPE TOWN	29	18	28	29		58	48	29		08	09	29		39	03	06	09 29
DURBAN	38																
DURBAN	39	39				08	06	03	39	18	08	06	03	58	09	06	03 39
PORT ELIZABETH	48	58	48			18	58	48		08	18	58	48	39	03	06	09 58 48
BLOEMFONTEIN	58	58				18	58			39	03	06	09 58	08	09	58	
EAST LONDON	41	58	41			18	58	41		08	18	58	41	39	03	06	09 58 41
KLERKSDORP	02	58	02			18	58	02		39	03	06	02	08	06	02	
WITBANK	03	39	03			08	06	03		18	08	06	03	58	09	06	03
RANDBURG	68	18	16	68		58	18	16	68	39	03	06	09 19 68	08	09	19	68
ROSEBANK	11	18	19	11		08	18	19	11	58	18	19	11	39	03	06	09 19 11

PATHS WITH THE LOWEST UTILIZED PRIMARY HOPS

DESTINATION		ROUTING FROM SYSTEM 38 IN DURBAN															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	08				58	18	08		18	08			39	03	06	08
PRETORIA	09	08	09			58	09			39	03	06	09	18	19	09	
PRETORIA	06	08	06			58	09	06		39	03	06		18	08	06	
BRAAMFONTEIN	16	18	16			58	18	16		39	03	06	09 19 16	08	18	16	
BRAAMFONTEIN	18	18				58	18			08	18			39	03	06	08 18
BRAAMFONTEIN	19	18	19			08	09	19		39	03	06	09 19	58	18	19	
CAPE TOWN	28	18	28			58	48	28		39	03	06	28	08	06	28	
CAPE TOWN	29	18	28	29		08	09	29		39	03	06	09 29	58	48	28	29
DURBAN	38																
DURBAN	39	39				58	09	06	03 39	08	06	03	39	18	08	06	03 39
PORT ELIZABETH	48	58	48			08	18	58	48	18	58	48		39	03	06	09 58 48
BLOEMFONTEIN	58	58				08	02	58		18	58			39	03	06	09 58
EAST LONDON	41	58	41			18	58	41		08	18	58	41	39	03	06	09 58 41
KLERKSDORP	02	58	02			08	06	02		18	58	02		39	03	06	02
WITBANK	03	39	03			08	06	03		18	08	06	03	58	09	06	03
RANDBURG	68	18	16	68		08	09	19 68		39	03	06	09 19 68	58	18	16	68
ROSEBANK	11	18	19	11		08	18	19	11	39	03	06	09 19 11	58	18	19	11

SHORTEST PATHS

DESTINATION		ROUTING FROM SYSTEM 38 IN DURBAN															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	08				18	08			58	18	08		39	03	06	08
PRETORIA	09	08	09			58	09			18	19	09		39	03	06	09
PRETORIA	06	08	06			18	08	06		39	03	06		58	09	06	
BRAAMFONTEIN	16	18	16			08	18	16		58	18	16		39	03	06	09 19 16
BRAAMFONTEIN	18	18				08	18			58	18			39	03	06	08 18
BRAAMFONTEIN	19	18	19			08	09	19		58	18	19		39	03	06	09 19
CAPE TOWN	28	18	28			58	48	28		08	06	28		39	03	06	28
CAPE TOWN	29	18	28	29		08	09	29		58	48	28	29	39	03	06	09 29
DURBAN	38																
DURBAN	39	39				08	06	03	39	18	08	06	03	58	09	06	03 39
PORT ELIZABETH	48	58	48			18	58	48		08	18	58	48	39	03	06	09 58 48
BLOEMFONTEIN	58	58				18	58			18	09	58		39	03	06	09 58
EAST LONDON	41	58	41			58	41			18	58	41		08	18	58	41
KLERKSDORP	02	58	02			08	06	02		18	58	02		39	03	06	02
WITBANK	03	39	03			08	06	03		18	08	06	03	58	09	06	03
RANDBURG	68	18	16	68		08	09	19 68		58	18	16	68	39	03	06	09 19 68
ROSEBANK	11	18	19	11		08	18	19	11	58	18	19	11	39	03	06	09 19 11

MAXIMUM BANDWIDTH PATHS

DESTINATION		ROUTING FROM SYSTEM 39 IN DURBAN															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	38	08			03	06	08									
PRETORIA	09	38	08	09		03	06	09									
PRETORIA	06	03	06			38	08	06									
BRAAMFONTEIN	16	38	18	16		03	06	08	18	16							
BRAAMFONTEIN	18	38	18			03	06	08	18								
BRAAMFONTEIN	19	38	18	19		03	06	09	19								
CAPE TOWN	28	38	18	28		03	06	28									
CAPE TOWN	29	38	18	28	29	03	06	09	29								
DURBAN	38	38				03	06	08	38								
DURBAN	39																
PORT ELIZABETH	48	38	58	48		03	06	09	58	48							
BLOEMFONTEIN	58	38	58			03	06	09	58								
EAST LONDON	41	38	58	41		03	06	09	58	41							
KLERKSDORP	02	38	58	02		03	06	02									
WITBANK	03	03				38	08	06	03								
RANDBURG	68	38	18	16	68	03	06	09	19	68							
ROSEBANK	11	38	18	19	11	03	06	09	19	11							

MINIMUM ESTIMATED TIME DELAY PATHS

DESTINATION		ROUTING FROM SYSTEM 39 IN DURBAN															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	38	08			03	06	08									
PRETORIA	09	38	08	09		03	06	09									
PRETORIA	06	03	06			38	08	06									
BRAAMFONTEIN	16	38	18	16		03	06	08	18	16							
BRAAMFONTEIN	18	38	18			03	06	08	18								
BRAAMFONTEIN	19	38	18	19		03	06	09	19								
CAPE TOWN	28	38	18	28		03	06	28									
CAPE TOWN	29	38	18	28	29	03	06	09	29								
DURBAN	38	38				03	06	08	38								
DURBAN	39																
PORT ELIZABETH	48	38	58	48		03	06	09	58	48							
BLOEMFONTEIN	58	38	58			03	06	09	58								
EAST LONDON	41	38	58	41		03	06	09	58	41							
KLERKSDORP	02	38	58	02		03	06	02									
WITBANK	03	03				38	08	06	03								
RANDBURG	68	38	18	16	68	03	06	09	19	68							
ROSEBANK	11	38	18	19	11	03	06	09	19	11							

PATHS WITH THE LOWEST UTILIZED PRIMARY HOPS

DESTINATION		ROUTING FROM SYSTEM 39 IN DURBAN															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	38	08			03	06	08									
PRETORIA	09	38	08	09		03	06	09									
PRETORIA	06	03	06			38	08	06									
BRAAMFONTEIN	16	38	18	16		03	06	08	18	16							
BRAAMFONTEIN	18	38	18			03	06	08	18								
BRAAMFONTEIN	19	38	18	19		03	06	09	19								
CAPE TOWN	28	38	18	28		03	06	28									
CAPE TOWN	29	38	18	28	29	03	06	09	29								
DURBAN	38	38				03	06	08	38								
DURBAN	39																
PORT ELIZABETH	48	38	58	48		03	06	09	58	48							
BLOEMFONTEIN	58	38	58			03	06	09	58								
EAST LONDON	41	38	58	41		03	06	09	58	41							
KLERKSDORP	02	38	58	02		03	06	02									
WITBANK	03	03				38	08	06	03								
RANDBURG	68	38	18	16	68	03	06	09	19	68							
ROSEBANK	11	38	18	19	11	03	06	09	19	11							

SHORTEST PATHS

DESTINATION		ROUTING FROM SYSTEM 39 IN DURBAN															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	38	08			03	06	08									
PRETORIA	09	38	08	09		03	06	09									
PRETORIA	06	03	06			38	08	06									
BRAAMFONTEIN	16	38	18	16		03	06	08	18	16							
BRAAMFONTEIN	18	38	18			03	06	08	18								
BRAAMFONTEIN	19	38	18	19		03	06	09	19								
CAPE TOWN	28	38	18	28		03	06	28									
CAPE TOWN	29	38	18	28	29	03	06	09	29								
DURBAN	38	38				03	06	08	38								
DURBAN	39																
PORT ELIZABETH	48	38	58	48		03	06	09	58	48							
BLOEMFONTEIN	58	38	58			03	06	09	58								
EAST LONDON	41	38	58	41		03	06	09	58	41							
KLERKSDORP	02	38	58	02		03	06	02									
WITBANK	03	03				38	08	06	03								
RANDBURG	68	38	18	16	68	03	06	09	19	68							
ROSEBANK	11	38	18	19	11	03	06	09	19	11							

MAXIMUM BANDWIDTH PATHS

DESTINATION		ROUTING FROM SYSTEM 48 IN PORT ELIZABETH															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	58	18	08		41	58	18	08	28	06	08					
PRETORIA	09	58	09			41	58	09		28	29	09					
PRETORIA	06	58	09	06		28	06			41	58	09	06				
BRAAMFONTEIN	16	58	18	16		41	58	18	16	28	29	16					
BRAAMFONTEIN	19	58	18			28	18			41	58	18					
BRAAMFONTEIN	19	58	18	19		41	58	18	19	28	18	19					
CAPE TOWN	28	28				41	58	18	28	58	18	28					
CAPE TOWN	29	28	29			41	58	09	29	58	09	29					
DURBAN	38	58	38			41	58	38		28	18	38					
DURBAN	39	58	38	39		41	58	38	39	28	18	38	39				
PORT ELIZABETH	48																
BLOEMFONTEIN	58	58				41	58			28	18	58					
EAST LONDON	41	41				28	18	58	41	58	41						
KLERKSDOORP	02	58	02			28	06	02		41	58	02					
WITBANK	03	58	09	06	03	28	06	03		41	58	09	06	03			
RANDBURG	68	58	18	16	68	41	58	18	16	68	28	18	16	68			
ROSEBANK	11	58	18	19	11	41	58	18	19	11	28	18	19	11			

MINIMUM ESTIMATED TIME DELAY PATHS

DESTINATION		ROUTING FROM SYSTEM 48 IN PORT ELIZABETH															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	58	18	08		28	06	08		41	58	18	08				
PRETORIA	09	58	09			41	58	09		28	29	09					
PRETORIA	06	58	09	06		28	06			41	58	09	06				
BRAAMFONTEIN	16	58	18	16		28	29	16		41	58	18	16				
BRAAMFONTEIN	18	58	18			28	18			41	58	18					
BRAAMFONTEIN	19	58	18	19		41	58	18	19	28	18	19					
CAPE TOWN	28	28				41	58	18	28	58	18	28					
CAPE TOWN	29	28	29			41	58	09	29	58	09	29					
DURBAN	38	58	38			41	58	38		28	18	38					
DURBAN	39	58	38	39		41	58	38	39	28	18	38	39				
PORT ELIZABETH	48																
BLOEMFONTEIN	58	58				41	58			28	18	58					
EAST LONDON	41	41				58	41			28	18	58	41				
KLERKSDOORP	02	58	02			41	58	02		28	06	02					
WITBANK	03	58	09	06	03	28	06	03		41	58	09	06	03			
RANDBURG	68	58	18	16	68	41	58	18	16	68	28	18	16	68			
ROSEBANK	11	58	18	19	11	41	58	18	19	11	28	18	19	11			

PATHS WITH THE LOWEST UTILIZED PRIMARY HOPS

DESTINATION		ROUTING FROM SYSTEM 48 IN PORT ELIZABETH															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	58	18	08		41	58	18	08	28	06	08					
PRETORIA	09	58	09			41	58	09		28	29	09					
PRETORIA	06	58	09	06		28	06			41	58	09	06				
BRAAMFONTEIN	16	58	18	16		41	58	18	16	28	29	16					
BRAAMFONTEIN	18	58	18			41	58	18		28	18						
BRAAMFONTEIN	19	58	18	19		28	18	19		41	58	18	19				
CAPE TOWN	28	28				41	58	18	28	58	18	28					
CAPE TOWN	29	28	29			41	58	09	29	58	09	29					
DURBAN	38	58	38			41	58	38		28	18	38					
DURBAN	39	58	38	39		41	58	38	39	28	18	38	39				
PORT ELIZABETH	48																
BLOEMFONTEIN	58	58				41	58			28	18	58					
EAST LONDON	41	41				28	18	58	41	58	41						
KLERKSDOORP	02	58	02			41	58	02		28	06	02					
WITBANK	03	58	09	06	03	41	58	09	06	03	28	06	03				
RANDBURG	68	58	18	16	68	41	58	18	16	68	28	18	16	68			
ROSEBANK	11	58	18	19	11	41	58	18	19	11	28	18	19	11			

SHORTEST PATHS

DESTINATION		ROUTING FROM SYSTEM 48 IN PORT ELIZABETH															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	58	18	08		41	58	18	08	28	06	08					
PRETORIA	09	58	09			41	58	09		28	29	09					
PRETORIA	06	58	09	06		28	06			41	58	09	06				
BRAAMFONTEIN	16	58	18	16		41	58	18	16	28	29	16					
BRAAMFONTEIN	18	58	18			41	58	18		28	18						
BRAAMFONTEIN	19	58	18	19		41	58	18	19	28	18	19					
CAPE TOWN	28	28				58	18	28		41	58	18	28				
CAPE TOWN	29	28	29			58	09	29		41	58	09	29				
DURBAN	38	58	38			41	58	38		28	18	38					
DURBAN	39	58	38	39		41	58	38	39	28	18	38	39				
PORT ELIZABETH	48																
BLOEMFONTEIN	58	58				41	58			28	18	58					
EAST LONDON	41	41				58	41			28	18	58	41				
KLERKSDOORP	02	58	02			41	58	02		28	06	02					
WITBANK	03	58	09	06	03	28	06	03		41	58	09	06	03			
RANDBURG	68	58	18	16	68	41	58	18	16	68	28	18	16	68			
ROSEBANK	11	58	18	19	11	41	58	18	19	11	28	18	19	11			

MAXIMUM BANDWIDTH PATHS

DESTINATION		ROUTING FROM SYSTEM 58 IN BLOEMFONTEIN															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	18	08			38	08			09	08			02	06	08	
PRETORIA	09	09				48	28	29	09	41	48	28	29	18	19	09	
PRETORIA	06	09	06			02	06			41	48	28	06	48	28	06	
BRAAMFONTEIN	16	18	16			09	19	16		38	18	16		02	06	09	19
BRAAMFONTEIN	18	18				38	18			48	28	18		41	48	28	18
BRAAMFONTEIN	19	18	19			09	19			38	18	19		48	28	18	19
CAPE TOWN	28	48	28			02	06	28		38	18	28		18	28		
CAPE TOWN	29	48	28	29		09	29			18	28	29		41	48	28	29
DURBAN	38	38				18	38			48	28	18	38	09	08	38	
DURBAN	39	38	39			02	06	03	39	18	38	39		09	08	38	39
PORT ELIZABETH	48	48				18	28	48		41	48			02	06	28	48
BLOEMFONTEIN	58																
EAST LONDON	41	41				02	06	28	48	18	28	48	41	48	41		
KLERKSDORP	02	02				41	48	28	06	48	28	06	02	18	08	06	02
WITBANK	03	09	06	03		02	06	03		48	28	06	03	41	48	28	06
RANDBURG	68	18	16	68		09	19	68		38	18	16	68	02	06	09	19
ROSEBANK	11	18	19	11		09	19	11		38	18	19	11	02	06	09	19

MINIMUM ESTIMATED TIME DELAY PATHS

DESTINATION		ROUTING FROM SYSTEM 58 IN BLOEMFONTEIN															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	18	08			38	08			09	08			48	28	06	08
PRETORIA	09	09				02	06	09		38	08	09		18	19	09	
PRETORIA	06	09	06			02	06			48	28	06		18	08	06	
BRAAMFONTEIN	16	18	16			09	19	16		38	18	16		09	19	16	
BRAAMFONTEIN	18	18				38	18			48	28	18		09	08	18	
BRAAMFONTEIN	19	18	19			09	19			38	18	19		48	28	18	19
CAPE TOWN	28	48	28			02	06	28		18	28			38	18	28	
CAPE TOWN	29	48	28	29		09	29			18	28	29		41	48	28	29
DURBAN	38	38				18	38			02	06	08	38	09	08	38	
DURBAN	39	38	39			02	06	03	39	09	08	38	39	18	38	39	
PORT ELIZABETH	48	48				41	48			02	06	28	48	18	28	48	
BLOEMFONTEIN	58																
EAST LONDON	41	41				48	41			18	28	48	41	02	06	28	48
KLERKSDORP	02	02				38	08	06	02	41	48	28	06	18	08	06	02
WITBANK	03	09	06	03		02	06	03		38	39	03		41	48	28	06
RANDBURG	68	18	16	68		09	19	68		38	18	16	68	02	06	09	19
ROSEBANK	11	18	19	11		09	19	11		38	18	19	11	48	28	18	19

PATHS WITH THE LOWEST UTILIZED PRIMARY HOPS

DESTINATION		ROUTING FROM SYSTEM 58 IN BLOEMFONTEIN															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	18	08			38	08			41	48	28	06	48	28	06	08
PRETORIA	09	09				02	06	09		38	08	09		18	19	09	
PRETORIA	06	09	06			02	06			41	48	28	06	38	08	06	
BRAAMFONTEIN	16	18	16			38	18	16		41	48	28	29	48	28	29	16
BRAAMFONTEIN	18	18				02	06	08	18	41	48	28	18	09	08	18	
BRAAMFONTEIN	19	18	19			38	18	19		48	28	18	19	41	48	28	18
CAPE TOWN	28	48	28			38	18	28		09	29	28		18	28		
CAPE TOWN	29	48	28	29		38	18	28	29	09	29			18	28	29	
DURBAN	38	38				02	06	08	38	18	38			48	28	18	38
DURBAN	39	38	39			02	06	03	39	18	38	39		09	08	38	39
PORT ELIZABETH	48	48				02	06	28	48	09	29	28	48	18	28	48	
BLOEMFONTEIN	58																
EAST LONDON	41	41				02	06	28	48	18	28	48	41	48	41		
KLERKSDORP	02	02				38	08	06	02	41	48	28	06	09	06	02	
WITBANK	03	09	06	03		02	06	03		38	39	03		48	28	06	03
RANDBURG	68	18	16	68		38	18	16	68	02	06	09	19	48	28	18	19
ROSEBANK	11	18	19	11		38	18	19	11	02	06	09	19	48	28	18	19

SHORTEST PATHS

DESTINATION		ROUTING FROM SYSTEM 58 IN BLOEMFONTEIN															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	09	08			18	08			02	06	08		38	08		
PRETORIA	09	09				18	19	09		02	06	09		38	08	09	
PRETORIA	06	09	06			02	06			18	08	06		38	08	06	
BRAAMFONTEIN	16	18	16			09	19	16		38	18	16		02	06	09	19
BRAAMFONTEIN	18	18				09	08	18		38	18			02	06	08	18
BRAAMFONTEIN	19	18	19			09	19			38	18	19		02	06	09	19
CAPE TOWN	28	48	28			18	28			41	48	28		09	29	28	
CAPE TOWN	29	48	28	29		09	29			18	28	29		41	48	28	29
DURBAN	38	38				18	38			09	08	38		02	06	08	38
DURBAN	39	38	39			18	38	39		09	08	38	39	02	06	03	39
PORT ELIZABETH	48	48				41	48			18	28	48		09	29	28	48
BLOEMFONTEIN	58																
EAST LONDON	41	41				48	41			18	28	48	41	09	29	28	48
KLERKSDORP	02	02				09	06	02		18	08	06	02	48	28	06	02
WITBANK	03	09	06	03		02	06	03		38	39	03		18	08	06	03
RANDBURG	68	18	16	68		09	19	68		38	18	16	68	02	06	09	19
ROSEBANK	11	18	19	11		09	19	11		38	18	19	11	02	06	09	19

MAXIMUM BANDWIDTH PATHS

DESTINATION		ROUTING FROM SYSTEM 41 IN EAST LONDON															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	58	18	08		48	58	18	08								
PRETORIA	09	58	09			48	58	09									
PRETORIA	06	58	09	06		48	58	09	06								
BRAAMFONTEIN	16	58	18	16		48	58	18	16								
BRAAMFONTEIN	18	58	18			48	58	18									
BRAAMFONTEIN	19	58	18	19		48	58	18	19								
CAPE TOWN	28	48	28			58	48	28									
CAPE TOWN	29	48	28	29		58	48	28	29								
DURBAN	38	58	38			48	58	38									
DURBAN	39	58	38	39		48	58	38	39								
PORT ELIZABETH	48	48				58	48										
BLOEMFONTEIN	58	58				48	58										
EAST LONDON	41																
KLERKSDORP	02	58	02			48	58	02									
WITBANK	03	58	09	06	03	48	58	09	06	03							
RANDBURG	68	58	18	16	68	48	58	18	16	68							
ROSEBANK	11	58	18	19	11	48	58	18	19	11							

MINIMUM ESTIMATED TIME DELAY PATHS

DESTINATION		ROUTING FROM SYSTEM 41 IN EAST LONDON															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	58	18	08		48	58	18	08								
PRETORIA	09	58	09			48	58	09									
PRETORIA	06	58	09	06		48	58	09	06								
BRAAMFONTEIN	16	58	18	16		48	58	18	16								
BRAAMFONTEIN	18	58	18			48	58	18									
BRAAMFONTEIN	19	58	18	19		48	58	18	19								
CAPE TOWN	28	48	28			58	48	28									
CAPE TOWN	29	48	28	29		58	48	28	29								
DURBAN	38	58	38			48	58	38									
DURBAN	39	58	38	39		48	58	38	39								
PORT ELIZABETH	48	48				58	48										
BLOEMFONTEIN	58	58				48	58										
EAST LONDON	41																
KLERKSDORP	02	58	02			48	58	02									
WITBANK	03	58	09	06	03	48	58	09	06	03							
RANDBURG	68	58	18	16	68	48	58	18	16	68							
ROSEBANK	11	58	18	19	11	48	58	18	19	11							

PATHS WITH THE LOWEST UTILIZED PRIMARY HOPS

DESTINATION		ROUTING FROM SYSTEM 41 IN EAST LONDON															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	58	18	08		48	58	18	08								
PRETORIA	09	58	09			48	58	09									
PRETORIA	06	58	09	06		48	58	09	06								
BRAAMFONTEIN	16	58	18	16		48	58	18	16								
BRAAMFONTEIN	18	58	18			48	58	18									
BRAAMFONTEIN	19	58	18	19		48	58	18	19								
CAPE TOWN	28	48	28			58	48	28									
CAPE TOWN	29	48	28	29		58	48	28	29								
DURBAN	38	58	38			48	58	38									
DURBAN	39	58	38	39		48	58	38	39								
PORT ELIZABETH	48	48				58	48										
BLOEMFONTEIN	58	58				48	58										
EAST LONDON	41																
KLERKSDORP	02	58	02			48	58	02									
WITBANK	03	58	09	06	03	48	58	09	06	03							
RANDBURG	68	58	18	16	68	48	58	18	16	68							
ROSEBANK	11	58	18	19	11	48	58	18	19	11							

SHORTEST PATHS

DESTINATION		ROUTING FROM SYSTEM 41 IN EAST LONDON															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	58	18	08		48	58	18	08								
PRETORIA	09	58	09			48	58	09									
PRETORIA	06	58	09	06		48	58	09	06								
BRAAMFONTEIN	16	58	18	16		48	58	18	16								
BRAAMFONTEIN	18	58	18			48	58	18									
BRAAMFONTEIN	19	58	18	19		48	58	18	19								
CAPE TOWN	28	48	28			58	48	28									
CAPE TOWN	29	48	28	29		58	48	28	29								
DURBAN	38	58	38			48	58	38									
DURBAN	39	58	38	39		48	58	38	39								
PORT ELIZABETH	48	48				58	48										
BLOEMFONTEIN	58	58				48	58										
EAST LONDON	41																
KLERKSDORP	02	58	02			48	58	02									
WITBANK	03	58	09	06	03	48	58	09	06	03							
RANDBURG	68	58	18	16	68	48	58	18	16	68							
ROSEBANK	11	58	18	19	11	48	58	18	19	11							

MAXIMUM BANDWIDTH PATHS

DESTINATION		ROUTING FROM SYSTEM 02 IN KLERKSDORP															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	06	08			58	09	06									
PRETORIA	09	06	09			58	09										
PRETORIA	06	06				58	09	06									
BRAAMFONTEIN	16	58	18	16		06	09	19	16								
BRAAMFONTEIN	18	58	18			06	08	18									
BRAAMFONTEIN	19	06	09	19		58	18	19									
CAPE TOWN	28	06	28			58	48	28									
CAPE TOWN	29	06	09	29		58	48	28	29								
DURBAN	38	58	38			06	08	38									
DURBAN	39	58	38	39		06	08	38	39								
PORT ELIZABETH	48	58	48			06	09	58	48								
BLOEMFONTEIN	58	58				06	09	58									
EAST LONDON	41	58	41			06	09	58	41								
KLERKSDORP	02																
WITBANK	03	06	03			58	08	06	03								
RANDBURG	68	06	09	19	68	58	18	16	68								
ROSEBANK	11	06	09	19	11	58	18	19	11								

MINIMUM ESTIMATED TIME DELAY PATHS

DESTINATION		ROUTING FROM SYSTEM 02 IN KLERKSDORP															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	06	08			58	09	08									
PRETORIA	09	06	09			58	09										
PRETORIA	06	06				58	09	06									
BRAAMFONTEIN	16	58	18	16		06	09	19	16								
BRAAMFONTEIN	18	58	18			06	08	18									
BRAAMFONTEIN	19	06	09	19		58	18	19									
CAPE TOWN	28	06	28			58	48	28									
CAPE TOWN	29	06	09	29		58	48	28	29								
DURBAN	38	58	38			06	08	38									
DURBAN	39	58	38	39		06	08	38	39								
PORT ELIZABETH	48	58	48			06	09	58	48								
BLOEMFONTEIN	58	58				06	09	58									
EAST LONDON	41	58	41			06	09	58	41								
KLERKSDORP	02																
WITBANK	03	06	03			58	08	06	03								
RANDBURG	68	06	09	19	68	58	18	16	68								
ROSEBANK	11	06	09	19	11	58	18	19	11								

PATHS WITH THE LOWEST UTILIZED PRIMARY HOPS

DESTINATION		ROUTING FROM SYSTEM 02 IN KLERKSDORP															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	06	08			58	09	08									
PRETORIA	09	06	09			58	09										
PRETORIA	06	06				58	09	06									
BRAAMFONTEIN	16	58	18	16		06	09	19	16								
BRAAMFONTEIN	18	58	18			06	08	18									
BRAAMFONTEIN	19	06	09	19		58	18	19									
CAPE TOWN	28	06	28			58	48	28									
CAPE TOWN	29	06	09	29		58	48	28	29								
DURBAN	38	58	38			06	08	38									
DURBAN	39	58	38	39		06	08	38	39								
PORT ELIZABETH	48	58	48			06	09	58	48								
BLOEMFONTEIN	58	58				06	09	58									
EAST LONDON	41	58	41			06	09	58	41								
KLERKSDORP	02																
WITBANK	03	06	03			58	08	06	03								
RANDBURG	68	06	09	19	68	58	18	16	68								
ROSEBANK	11	06	09	19	11	58	18	19	11								

SHORTEST PATHS

DESTINATION		ROUTING FROM SYSTEM 02 IN KLERKSDORP															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	06	08			58	09	08									
PRETORIA	09	06	09			58	09										
PRETORIA	06	06				58	09	06									
BRAAMFONTEIN	16	58	18	16		06	09	19	16								
BRAAMFONTEIN	18	58	18			06	08	18									
BRAAMFONTEIN	19	06	09	19		58	18	19									
CAPE TOWN	28	06	28			58	48	28									
CAPE TOWN	29	06	09	29		58	48	28	29								
DURBAN	38	58	38			06	08	38									
DURBAN	39	58	38	39		06	08	38	39								
PORT ELIZABETH	48	58	48			06	09	58	48								
BLOEMFONTEIN	58	58				06	09	58									
EAST LONDON	41	58	41			06	09	58	41								
KLERKSDORP	02																
WITBANK	03	06	03			58	08	06	03								
RANDBURG	68	06	09	19	68	58	18	16	68								
ROSEBANK	11	06	09	19	11	58	18	19	11								

MAXIMUM BANDWITH PATHS

DESTINATION		ROUTING FROM SYSTEM 03 IN WITBANK															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	06	08			39	38	08									
PRETORIA	09	06	09			39	38	08	09								
PRETORIA	06	06				39	38	08	06								
BRAAMFONTEIN	16	06	08	18	16	39	38	18	16								
BRAAMFONTEIN	18	06	08	18		39	38	18									
BRAAMFONTEIN	19	06	09	19		39	38	18	19								
CAPE TOWN	28	06	28			39	38	18	28								
CAPE TOWN	29	06	09	29		39	38	18	28	29							
DURBAN	38	39	38			06	08	38									
DURBAN	39	39				06	08	38	39								
PORT ELIZABETH	48	06	08	58	48	39	38	58	48								
BLOEMFONTEIN	58	06	09	58		39	38	58									
EAST LONDON	41	06	09	58	41	39	38	58	41								
KLERKSDORP	02	06	02			39	38	58	02								
WITBANK	03																
RANDBURG	68	06	09	19	68	39	38	18	16	68							
ROSEBANK	11	06	09	19	11	39	38	18	19	11							

MINIMUM ESTIMATED TIME DELAY PATHS

DESTINATION		ROUTING FROM SYSTEM 03 IN WITBANK															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	06	08			39	38	08									
PRETORIA	09	06	09			39	38	08	09								
PRETORIA	06	06				39	38	08	06								
BRAAMFONTEIN	16	06	08	18	16	39	38	18	16								
BRAAMFONTEIN	18	06	08	18		39	38	18									
BRAAMFONTEIN	19	06	09	19		39	38	18	19								
CAPE TOWN	28	06	28			39	38	18	28								
CAPE TOWN	29	06	09	29		39	38	18	28	29							
DURBAN	38	39	38			06	08	38									
DURBAN	39	39				06	08	38	39								
PORT ELIZABETH	48	06	08	58	48	39	38	58	48								
BLOEMFONTEIN	58	06	09	58		39	38	58									
EAST LONDON	41	06	09	58	41	39	38	58	41								
KLERKSDORP	02	06	02			39	38	58	02								
WITBANK	03																
RANDBURG	68	06	09	19	68	39	38	18	16	68							
ROSEBANK	11	06	09	19	11	39	38	18	19	11							

PATHS WITH THE LOWEST UTILIZED PRIMARY HOPS

DESTINATION		ROUTING FROM SYSTEM 03 IN WITBANK															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	06	08			39	38	08									
PRETORIA	09	06	09			39	38	08	09								
PRETORIA	06	06				39	38	08	06								
BRAAMFONTEIN	16	06	08	18	16	39	38	18	16								
BRAAMFONTEIN	18	06	08	18		39	38	18									
BRAAMFONTEIN	19	06	09	19		39	38	18	19								
CAPE TOWN	28	06	28			39	38	18	28								
CAPE TOWN	29	06	09	29		39	38	18	28	29							
DURBAN	38	39	38			06	08	38									
DURBAN	39	39				06	08	38	39								
PORT ELIZABETH	48	06	08	58	48	39	38	58	48								
BLOEMFONTEIN	58	06	09	58		39	38	58									
EAST LONDON	41	06	09	58	41	39	38	58	41								
KLERKSDORP	02	06	02			39	38	58	02								
WITBANK	03																
RANDBURG	68	06	09	19	68	39	38	18	16	68							
ROSEBANK	11	06	09	19	11	39	38	18	19	11							

SHORTEST PATHS

DESTINATION		ROUTING FROM SYSTEM 03 IN WITBANK															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	06	08			39	38	08									
PRETORIA	09	06	09			39	38	08	09								
PRETORIA	06	06				39	38	08	06								
BRAAMFONTEIN	16	06	08	18	16	39	38	18	16								
BRAAMFONTEIN	18	06	08	18		39	38	18									
BRAAMFONTEIN	19	06	09	19		39	38	18	19								
CAPE TOWN	28	06	28			39	38	18	28								
CAPE TOWN	29	06	09	29		39	38	18	28	29							
DURBAN	38	39	38			06	08	38									
DURBAN	39	39				06	08	38	39								
PORT ELIZABETH	48	06	08	58	48	39	38	58	48								
BLOEMFONTEIN	58	06	09	58		39	38	58									
EAST LONDON	41	06	09	58	41	39	38	58	41								
KLERKSDORP	02	06	02			39	38	58	02								
WITBANK	03																
RANDBURG	68	06	09	19	68	39	38	18	16	68							
ROSEBANK	11	06	09	19	11	39	38	18	19	11							

MAXIMUM BANDWIDTH PATHS

DESTINATION		ROUTING FROM SYSTEM 68 IN RANDBURG															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	16	18	08		19	09	08									
PRETORIA	09	19	09			16	19	09									
PRETORIA	06	19	09	06		16	18	08	06								
BRAAMFONTEIN	16	16				19	16										
BRAAMFONTEIN	18	16	18			19	18										
BRAAMFONTEIN	19	19				16	19										
CAPE TOWN	28	19	18	28		16	29	28									
CAPE TOWN	29	16	29			19	16	29									
DURBAN	38	16	18	38		19	18	38									
DURBAN	39	16	18	38	39	19	18	38	39								
PORT ELIZABETH	48	16	18	58	48	19	18	58	48								
BLOEMFONTEIN	58	16	18	58		19	18	58									
EAST LONDON	41	16	18	58	41	19	18	58	41								
KLERKSDORP	02	19	09	06	02	16	18	58	02								
WITBANK	03	19	09	06	03	16	18	08	06	03							
RANDBURG	68																
ROSEBANK	11	16	11			19	11										

MINIMUM ESTIMATED TIME DELAY PATHS

DESTINATION		ROUTING FROM SYSTEM 68 IN RANDBURG															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	16	18	08		19	09	08									
PRETORIA	09	19	09			16	19	09									
PRETORIA	06	19	09	06		16	18	08	06								
BRAAMFONTEIN	16	16				19	16										
BRAAMFONTEIN	18	16	18			19	18										
BRAAMFONTEIN	19	19				16	19										
CAPE TOWN	28	19	18	28		16	29	28									
CAPE TOWN	29	16	29			19	16	29									
DURBAN	38	16	18	38		19	18	38									
DURBAN	39	16	18	38	39	19	18	38	39								
PORT ELIZABETH	48	16	18	58	48	19	18	58	48								
BLOEMFONTEIN	58	16	18	58		19	18	58									
EAST LONDON	41	16	18	58	41	19	18	58	41								
KLERKSDORP	02	19	09	06	02	16	18	58	02								
WITBANK	03	19	09	06	03	16	18	08	06	03							
RANDBURG	68																
ROSEBANK	11	16	11			19	11										

PATHS WITH THE LOWEST UTILIZED PRIMARY HOPS

DESTINATION		ROUTING FROM SYSTEM 68 IN RANDBURG															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	19	09	08		16	18	09									
PRETORIA	09	19	09			16	19	09									
PRETORIA	06	19	09	06		16	18	08	06								
BRAAMFONTEIN	16	16				19	16										
BRAAMFONTEIN	18	16	18			19	18										
BRAAMFONTEIN	19	19				16	19										
CAPE TOWN	28	19	18	28		16	29	28									
CAPE TOWN	29	16	29			19	16	29									
DURBAN	38	16	18	38		19	18	38									
DURBAN	39	16	18	38	39	19	18	38	39								
PORT ELIZABETH	48	19	18	58	48	16	18	58	48								
BLOEMFONTEIN	58	19	18	58		16	18	58									
EAST LONDON	41	16	18	58	41	19	18	58	41								
KLERKSDORP	02	19	09	06	02	16	18	58	02								
WITBANK	03	19	09	06	03	16	18	08	06	03							
RANDBURG	68																
ROSEBANK	11	16	11			19	11										

SHORTEST PATHS

DESTINATION		ROUTING FROM SYSTEM 68 IN RANDBURG															
DSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	16	18	08		19	09	08									
PRETORIA	09	19	09			16	19	09									
PRETORIA	06	19	09	06		16	18	08	06								
BRAAMFONTEIN	16	16				19	16										
BRAAMFONTEIN	18	16	18			19	18										
BRAAMFONTEIN	19	19				16	19										
CAPE TOWN	28	19	18	28		16	29	28									
CAPE TOWN	29	16	29			19	16	29									
DURBAN	38	16	18	38		19	18	38									
DURBAN	39	16	18	38	39	19	18	38	39								
PORT ELIZABETH	48	16	18	58	48	16	18	58	48								
BLOEMFONTEIN	58	16	18	58		19	18	58									
EAST LONDON	41	16	18	58	41	19	18	58	41								
KLERKSDORP	02	19	09	06	02	16	18	58	02								
WITBANK	03	19	09	06	03	16	18	08	06	03							
RANDBURG	68																
ROSEBANK	11	16	11			19	11										

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MAXIMUM BANDWIDTH PATHS

DESTINATION		ROUTING FROM SYSTEM 11 IN ROSEBANK															
OSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	19	18	08		16	18	08									
PRETORIA	09	19	09			16	19	09									
PRETORIA	06	19	09	06		16	19	09	06								
BRAAMFONTEIN	16	16				19	16										
BRAAMFONTEIN	18	19	18			16	18										
BRAAMFONTEIN	19	19				16	19										
CAPE TOWN	28	19	18	28		16	29	28									
CAPE TOWN	29	16	29			19	16	29									
DURBAN	38	16	18	38		19	18	38									
DURBAN	39	16	18	38	39	19	18	38	39								
PORT ELIZABETH	48	19	18	58	48	16	18	58	48								
BLOEMFONTEIN	58	19	18	58		16	18	58									
EAST LONDON	41	19	18	58	41	16	18	58	41								
KLERKSDORP	02	19	09	06	02	16	18	58	02								
WITBANK	03	19	09	06	03	16	19	09	06	03							
RANDBURG	68	16	68			19	68										
ROSEBANK	11																

MINIMUM ESTIMATED TIME DELAY PATHS

DESTINATION		ROUTING FROM SYSTEM 11 IN ROSEBANK															
OSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	19	18	08		16	18	08									
PRETORIA	09	19	09			16	19	09									
PRETORIA	06	19	09	06		16	19	09	06								
BRAAMFONTEIN	16	16				19	16										
BRAAMFONTEIN	18	19	18			16	18										
BRAAMFONTEIN	19	19				16	19										
CAPE TOWN	28	19	18	28		16	29	28									
CAPE TOWN	29	16	29			19	16	29									
DURBAN	38	16	18	38		19	18	38									
DURBAN	39	16	18	38	39	19	18	38	39								
PORT ELIZABETH	48	19	18	58	48	16	18	58	48								
BLOEMFONTEIN	58	19	18	58		16	18	58									
EAST LONDON	41	19	18	58	41	16	18	58	41								
KLERKSDORP	02	19	09	06	02	16	18	58	02								
WITBANK	03	19	09	06	03	16	19	09	06	03							
RANDBURG	68	16	68			19	68										
ROSEBANK	11																

PATHS WITH THE LOWEST UTILIZED PRIMARY HOPS

DESTINATION		ROUTING FROM SYSTEM 11 IN ROSEBANK															
OSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	19	18	08		16	18	08									
PRETORIA	09	19	09			16	19	09									
PRETORIA	06	19	09	06		16	19	09	06								
BRAAMFONTEIN	16	16				19	16										
BRAAMFONTEIN	18	19	18			16	18										
BRAAMFONTEIN	19	19				16	19										
CAPE TOWN	28	19	18	28		16	29	28									
CAPE TOWN	29	16	29			19	16	29									
DURBAN	38	16	18	38		19	18	38									
DURBAN	39	16	18	38	39	19	18	38	39								
PORT ELIZABETH	48	19	18	58	48	16	18	58	48								
BLOEMFONTEIN	58	19	18	58		16	18	58									
EAST LONDON	41	19	18	58	41	16	18	58	41								
KLERKSDORP	02	19	09	06	02	16	18	58	02								
WITBANK	03	19	09	06	03	16	19	09	06	03							
RANDBURG	68	16	68			19	68										
ROSEBANK	11																

SHORTEST PATHS

DESTINATION		ROUTING FROM SYSTEM 11 IN ROSEBANK															
OSE (NODE)	SYSTEM	1 st ROUTE				2 nd ROUTE				3 rd ROUTE				4 th ROUTE			
PRETORIA	08	19	18	08		16	18	08									
PRETORIA	09	19	09			16	19	09									
PRETORIA	06	19	09	06		16	19	09	06								
BRAAMFONTEIN	16	16				19	16										
BRAAMFONTEIN	18	19	18			16	18										
BRAAMFONTEIN	19	19				16	19										
CAPE TOWN	28	19	18	28		16	29	28									
CAPE TOWN	29	16	29			19	16	29									
DURBAN	38	16	18	38		19	18	38									
DURBAN	39	16	18	38	39	19	18	38	39								
PORT ELIZABETH	48	19	18	58	48	16	18	58	48								
BLOEMFONTEIN	58	19	18	58		16	18	58									
EAST LONDON	41	19	18	58	41	16	18	58	41								
KLERKSDORP	02	19	09	06	02	16	18	58	02								
WITBANK	03	19	09	06	03	16	19	09	06	03							
RANDBURG	68	16	68			19	68										
ROSEBANK	11																

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APPENDIX A

NETWORK ARCHITECTURE

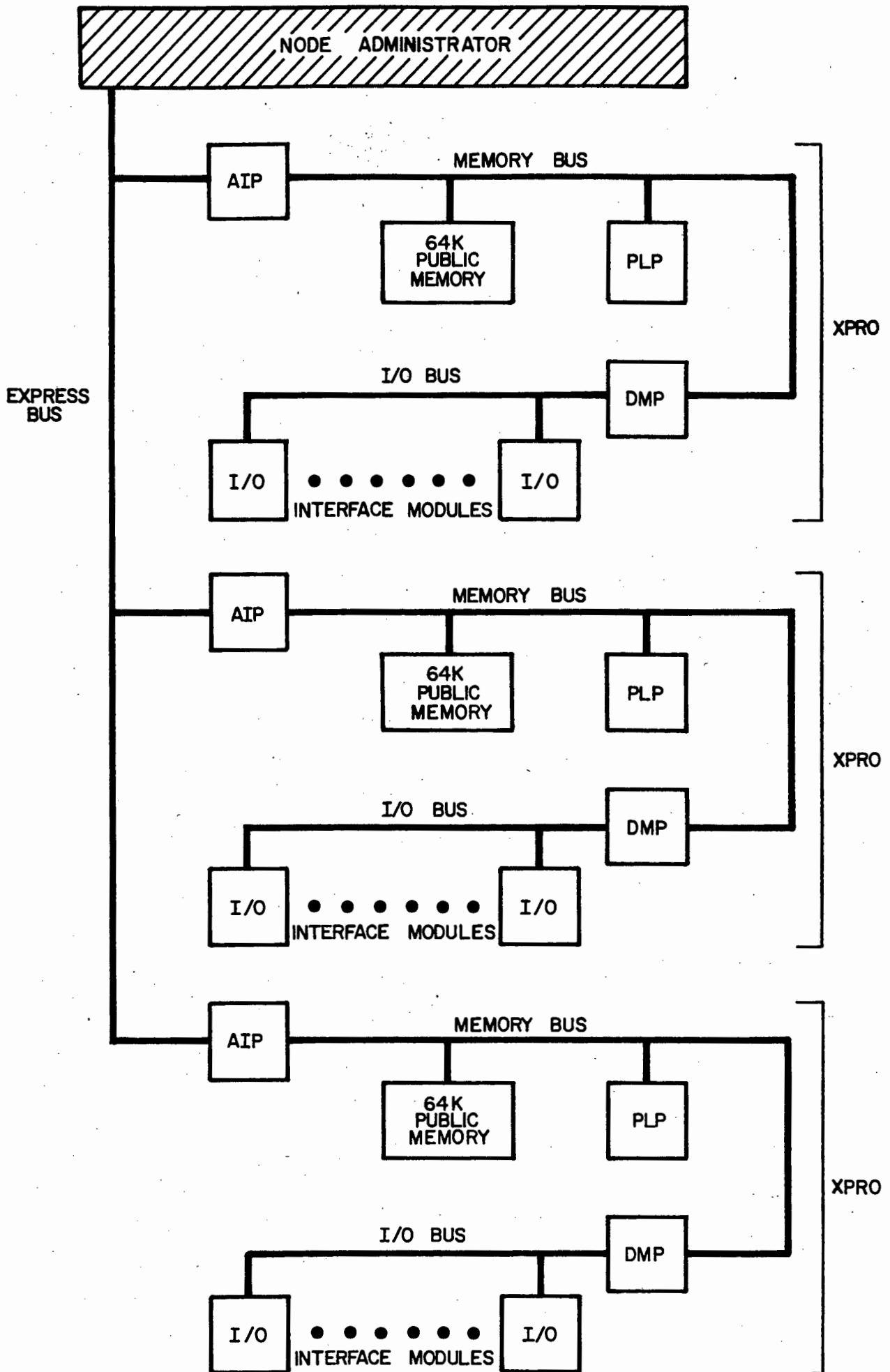
A.1 SWITCHING NODES

Switching nodes or Data Switching Exchanges (DSEs) provides a solution to perhaps the most challenging task that faces network providers today - the interconnection of many user devices from a variety of vendors. This interconnection may take the form of a simple installation serving only a few packet mode devices, or be expanded to a very large multinode network serving over 3500 such devices. The network which is presented to the user has a network access protocol and intranetwork protocol both supporting the virtual circuit technique. Additionally, the DSE system is a virtual circuit packet-switching system supporting the X.25 network access protocol and offers a wide range of user services as well as network design and management features providing an overall efficient and flexible data communications network.

Individual nodes (DSEs) contain a single node administrator and from one to three packet processor units. The packet processor units consists of an Administrator Interface Processor, a Packet Level Processor, a Data Movement Processor, X.25 Public Memory, and various channel interface modules (30, 31). (See FIGURE A-1 for the basic architecture of the 4410 network processor used by SAPONET).

A.1.1 Node Administrator

The node administrator is a minicomputer which verifies the call validity and defines routing connection throughout the



BASIC ARCHITECTURE OF 4410 NETWORK PROCESSOR

FIGURE A-1

network as well as the gathering and formatting of statistical, diagnostic and management reports for the entire node.

A.1.2 Administrator Interface Processor (AIP)

The administrator interface processor connects the packet processor modules to the node administrator.

The packet processor modules (XPROs) mainly consist of an Administrator Interface Processor, a Packet Level Processor, a Data Movement Processor, X25 Public Memory, and various channel interface modules. It provides a path for control information between the packet processor unit and the node administrator.

A.1.3 Packet Level Processor (PLP)

The primary function of the PLP is to handle the control of routing functions of the X25 packet-level protocol (see section A.4) and manage the X25 public memory. Up to seven different routes may be defined. A priority value is assigned to each route, allowing the preferred route to take priority over other routes when they are available. Routes may be defined to as many as 31 other nodes.

A.1.4 Data Movement Processor (DMP)

The data movement processor receives incoming packets and then transfers them to the X25 public memory for storage. The DMP also moves outgoing packets to the interface modules.

A.1.5 X25 Public Memory

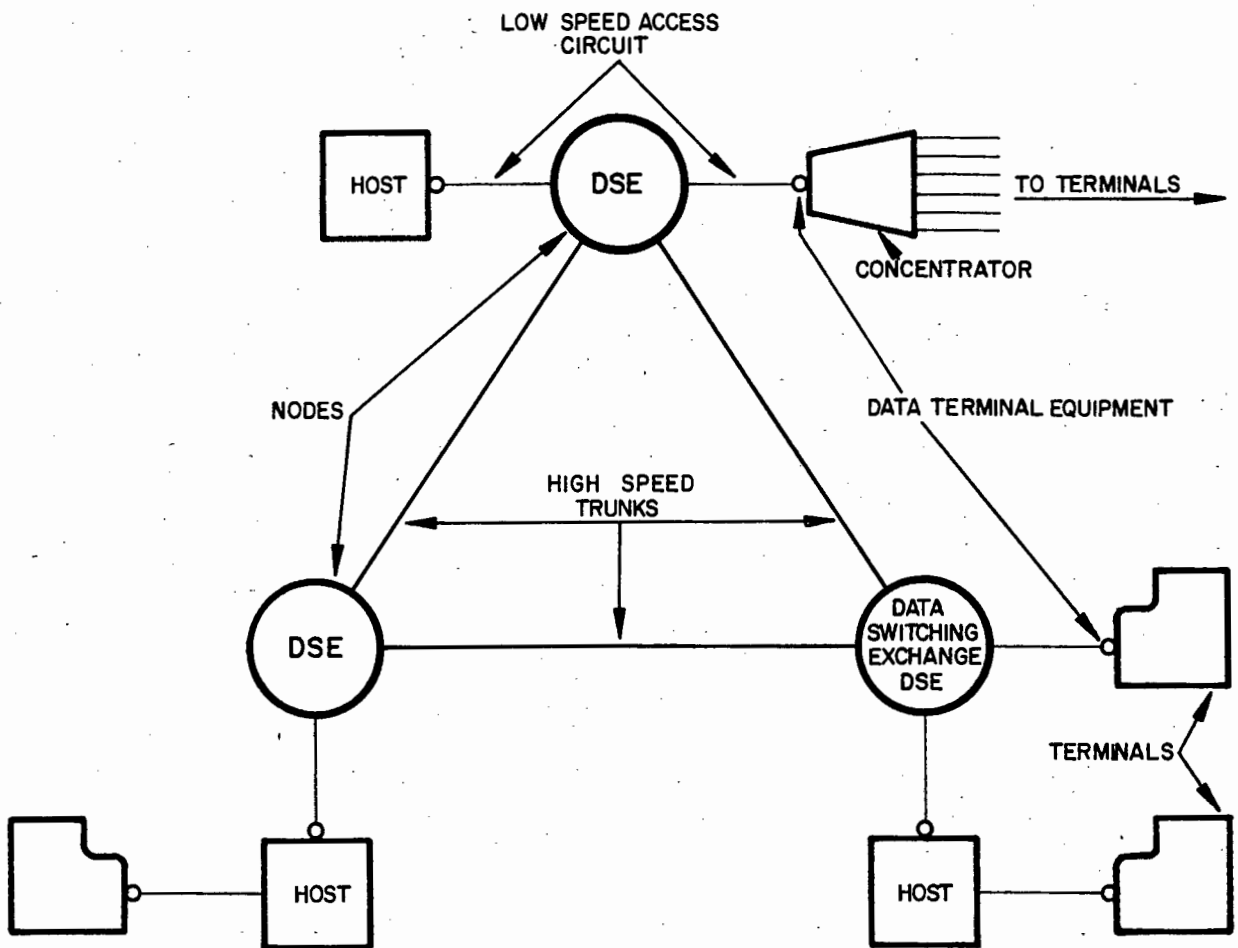
Each X25 packet processor contains a 16-bit 64 kiloword memory which provides buffers for inbound and outbound data packets as well as all the control information needed to handle the X25 protocol.

A.1.6 Interface Modules

Each packet processor unit permits the connection of over 50 packet-mode devices or protocol-translation units commonly referred to as DTE, or data terminal equipment (terminals, hosts, front-end processors, etc). The interface to each module is available for data rates from 1 200 to 19 200 b/s and a single channel-interface V35 module is used for data rates from 19 200 to 64 000 b/s. The interface modules are responsible for handling levels 1 and 2 of the X25 protocol (see section A.4).

A.2 TERMINALS

It is necessary to be able to differentiate between USER (or subscriber) terminals, HOSTS and concentrators all of which can be classified as terminals. A USER terminal is an unintelligent or intelligent keyboard/printer terminal through which the USER can either be connected directly or indirectly via a HOST or concentrator to the switching node by utilizing the basic packet-switching service supporting end-to-end interprocess communication and user services. The HOSTS themselves are machines which support USER application programs and have powerful storage and computing facilities (33). A concentrator supports a number of terminals and is the interface between the terminals and the switching node.



SIMPLE COMPUTER - COMMUNICATION NETWORK

FIGURE A-2

A.3 LINKS

In a packet-switched network the USER has a dedicated access circuit only to the first node in the network where the switching functions are performed (DSE) thereafter trunk-circuits are provided on a shared-demand basis. The access circuits from the user to the DSE and the trunks between DSEs can be described as individual physical data links that are connected in tandem to build up the source to destination communication path.

A simple computer-communication network indicating nodes, terminals and links is shown in FIGURE A-2.

A.4 NETWORK ACCESS PROTOCOL

The network access protocol for the packet switching network model described in FIGURE A-2 is referred to as X25 and is strictly a user-network-interface standard where the USER operates from a set of equipment referred to as the data terminal equipment DTE and the data circuit terminating equipment DCE, which is provided by the network supplier.

The X25 recommendation is essentially divided into three distinct levels of control procedures: (a) Level 1, the physical level which describes the physical, electrical, functional and procedural characteristics to establish, maintain and disconnect the physical link between the terminal DTE and the network (DCE). The level is concerned with the transmission of raw bits over the channel. (b) Level 2, the link level which describes the data link control procedures for data interchange between the terminal and the network operating over a physical level.

(c) Level 3, the packet level specifies the manner in which control information and USER data are structured into packets for transmission between the terminal and the network (32), (34).

APPENDIX B

MULTICOMMODITY FLOW DEFINITIONS

Network flow problems have appeared in the management science literature for many years often in connection with logistics problems. However, it has been widely recognized that network flow techniques are applicable to the design and analysis of communication networks as well. The advent of teleprocessing has spurred interest in this area, particularly since the transformation of information between computers gives promise of improved efficiency in the utilization of computer resources (37).

If we consider a network consisting of two nodes then a problem formulation can be defined to find the maximum flow from the source node N_s to the destination node N_d without violating the constraints $X_{ij} \leq b_{ij}$ on the arcs where X_{ij} is the flow on the arc between nodes i and j . If there are many sources and many destinations where the flow from any source can be sent to any destinations and if the restriction is made that the flow from certain sources must not be sent to certain destinations, then the problem is a multicommodity flow problem.

For a computer network, the commodities are packets of data to be transmitted through the network. Element $r_{k,i}$ in the traffic requirement matrix can be viewed as the amount of commodity i that is supplied from node k destined for node i . There are thus N commodities where N is the number of nodes in the network and each node demands exactly one distinct commodity and supplies $N-1$ others.

The multicommodity (MC) flow problem, in this case, consists of finding the routes for all such commodities which minimize a well-defined performance function (cost,

time delay) such that a set of constraints (channel capacities, flows) are satisfied. The most general MC problem can be expressed formally as follows:

Given: A network of N nodes and B arcs.

An $N \times N$ matrix $R = (r_{ij})$, the traffic requirement matrix.

Minimize: $P(\phi)$ where ϕ is the flow configuration and P is a well defined performance function.

APPENDIX C

GRAPH THEORY

A GRAPH consists of a set of elements called NODES and a set of ARCS connecting the nodes. The terms lines, branch, edge and in the context of this study, LINKS (HOPS) are also used in the literature instead of arc. If two nodes are directly connected then they are said to be ADJACENT whereas if they are only indirectly connected via one or more intermediate nodes then they are not adjacent.

Graphs can have the following two types of arcs: (i) a DIRECTED arc indicates that information can flow only in the direction indicated by the arrow in the arc which models simplex or unidirectional channel transmission. (ii) An UNDIRECTED arc indicates that information can flow bothways which models full-duplex channel transmission where flow can be accepted in both directions simultaneously or half-duplex channel transmission where flow can be accepted in either direction but in only one direction at a given instant. A graph containing only directed arcs is called a DIRECTED GRAPH and similarly, a graph containing only undirected arcs is called an UNDIRECTED GRAPH.

The DEGREE (OR VALENCE) of a node is the number of arcs ending there. A PATH is a sequence of adjacent nodes. The LENGTH of a path is the number of arcs it contains. There are no repeated nodes in a path.

If every node is reachable from every other node, that is, if there is a path between every pair of nodes, the graph is said to consist of ONE COMPONENT. A one component graph is also said to be CONNECTED. The ARC CONNECTIVITY between

two nodes X and Y is the minimum number of arcs that must be removed from the graph to disconnect X and Y. Two paths are said to be ARC-DISJOINT if they have no arcs in common and NODE-DISJOINT if they have no nodes in common.

Analogous to the arc connectivity between two nodes is NODE-CONNECTIVITY which is the minimum number of nodes whose removal will disconnect the two nodes. If there are two node disjoint paths between every pair of nodes then such networks are said to be TWO-CONNECTED and if there are three node disjoint paths between every pair of nodes then such networks are said to be THREE-CONNECTED etc.

APPENDIX D

THE FLOW AND NON-BIFURCATED FLOW-DEVIATION ALGORITHMS

D.1 THE FLOW DEVIATION ALGORITHM

The following properties of the optimal routing solution must be mentioned before introducing the FD algorithm (9), (13).

Property 1

The set of MC flows f satisfying the requirement matrix R is a convex polyhedron. The extreme points of such a polyhedron are called "extremal flows" and correspond to shortest route policies where the shortest route policy is a policy that routes each (i, j) commodity along the shortest (i, j) path, evaluated under an arbitrary assignment of lengths to the links.

Property 2

For a given MC flow f , the "length" of a link i can be defined as the partial derivative, i.e.

$$\text{length } i = L_i = \frac{\partial T}{\partial f_i} \quad \text{where } T \text{ is the average time delay expressed in equation 2.4}$$

Let ϕ be the shortest route flow associated with such link lengths and let $\tilde{f} = (1-\lambda)f + \lambda\phi$ be the convex combination of ϕ and f minimizing the delay T . ϕ represents the flow deviation of steepest descent for T and if the flow $\tilde{f}$ is deviated to $\tilde{f} = (1-\lambda)\tilde{f} + \lambda\phi$, the flow $\tilde{f}$ gives a smaller value of T as a hill descending process. If $T(\tilde{f}) = T(f)$, then $\tilde{f}$ is called stationery and the value of $\tilde{f}$ gives the optimum routing (9), (29).

The algorithm is as follows: (29)

Step 1: Find a feasible starting flow $\tilde{f}^0$, Let $P=0$ where P is the number of iterations.

Step 2: Compute $\phi(P)$, the shortest route flow corresponding to $l_i(P) = (\partial T / \partial f_i) f = f(P)$ for all $i=1,2,\dots,b$ where b is the number of links.

Step 3: A value of λ is found which minimizes
 $T[(1-\lambda)\tilde{f}(P) + \lambda\phi(P)]$
 Let $f^{(P+1)} = (1-\lambda)\tilde{f}(P) + \lambda\phi(P)$

Step 4: If $T(f^{(P)}) - T(f^{(P+1)}) < \epsilon$ STOP : $f^{(P)}$ is the optimum flow, otherwise let $P=P+1$ and GO TO STEP 2.

An important detail to note about the above FD method is that it recommends that commodities should be sent along more than one route which is fine if the network operates on a datagram protocol, but for virtual circuit operation a slightly different FD method is required and is explained in the following section.

D.2 THE NON-BIFURCATED FLOW-DEVIATION ALGORITHM

An MC flow is defined as non-bifurcated if each commodity flows along one route only. The introduction of this constraint reduces the set of feasible MC flows to a discrete set. Continuous techniques, like the FD method explained in D.1 cannot be used to solve the routing problem and therefore an efficient sub-optimum technique is required. In the case of large networks and where the elements r_{ij} of the requirement matrix R is not highly diversified from one another, a modification of the FD method can be successfully applied (36). If we assume the following:

- (i) "length" of link i can be defined as the partial derivative i.e.

$$\text{length } i = L_i = \frac{\partial T}{\partial f_i} \quad \text{where } T \text{ is the average time delay expressed in equation 2.4.}$$

- (ii) ϕ is the shortest routes associated with such link lengths.

- (iii) flow $\tilde{f}$ is non-bifurcated.

- (iv) that commodity (i,j) flows on route π_{ij} .

- (v) π'_{ij} is the shortest (i,j) route.

The modified FD method deviated a proper amount λr_{ij} ($\lambda=1$), of (ij) commodity from π_{ij} to π'_{ij} such that the performance $T(\lambda) = T[(1-\lambda)\tilde{f}^{(P)} + \lambda\phi^{(P)}]$ is minimized. Where $\tilde{f}$ contains π_{ij} and 0 contains π'_{ij} . The algorithm is as follows:

Step-1: Let $\tilde{f}^0$ be a starting feasible non-bifurcated flow, set $P=0$ where P is the number of iterations.

Step-2: Compute SR ($\tilde{f}^{(P)}$), the shortest routes corresponding to $l_i^{(P)} = \partial T / \partial f_i$ $f = f^{(P)}$ for all $i = 1, 2, \dots, b$ where b is the number of links.

Step-3: Set $\tilde{g} = \tilde{f}^{(P)}$
For each commodity (ij) :

3 (a) Let ϕ be the flow configuration obtained from $\tilde{g}$ by deviating commodity (ij) to the shortest route π'_{ij} given by SR ($\tilde{f}^{(P)}$)

3 (b) If ϕ is feasible and $T(\phi) < T(\tilde{g})$ GO TO 3 (c), otherwise GO TO 3 (d).

3 (c) $\tilde{g} = \phi$

3 (d) If all commodities (ij) have been processed, GO TO 4, otherwise, GO TO 3(a).

Step 4: If $\tilde{g} = \tilde{f}^{(P)}$, STOP. The FD method cannot improve the non-bifurcated solution any further, otherwise, let $\tilde{f}^{(P+1)} = \tilde{g}$ and, let $P = P+1$ and GO TO STEP 2.

Note:- This algorithm only determines the primary paths between all node pairs in the network.

APPENDIX E

DEFINITION OF TERMS USED IN THE ALGORITHMS

- i - Is the source node in a path, where i can be equal to any value from 1 to N but $\neq j$, where N is the number of nodes in the network.
- j - Is the destination node in a path, where j can be equal to any value from 1 to N but $\neq i$.
- (i,j) - Is a node pair combination where i is the source node and j is the destination node and $i \neq j$.
- ij - Is the path between source node i and destination node j.
- (i₀,i₁) - Is the primary hop of path ij.
- (i₁,i₂) - Is the secondary hop of path ij.
- (i_{k-1},i_k) - Is the kth hop of path ij (if i₁ = j then path ij is the direct path between nodes i and j).
- B_{ij} - Are the best alternative paths between all source and destination node-pair combinations (i,j) in ascending order of weighted length.

- $A\pi_{ij}$ - "Affected path" between nodes i and j . For the primary path algorithm these are two or more paths between specific source-to-destination node pairs (i,j) each connected via an equal number of intermediate nodes and equal lowest "weighted" distance. For the secondary path algorithm these are the primary paths whose primary hops are affected by a link down. For the tertiary path algorithm these are the source to destination node pair paths whose primary and secondary paths primary hops are affected by the two links that are down. For the fourth alternative path algorithm these are the source to destination node pair paths whose primary, secondary and tertiary path primary hops are affected by the three links that are down.
- $SR\pi_{ij}$ - Is the path taken between source node i and destination node j when any hop other than the primary hop of a primary, secondary or tertiary path chosen has been affected by disconnected links.
- WN - Is the "working node" where for the tertiary path algorithm it is defined as a node (with a valence of 3) in the network which has three or more other nodes connected directly to it and for the fourth alternative path algorithm it is defined as a node (with a valence of 4) in the network which has four or more other nodes connected directly to it.

APPENDIX F

FEASIBLE PATH ALGORITHM

The following is a basic outline of the program used to determine all the feasible paths between all node pairs within a network:

Program:

- Step 1 : Read in the input data as follows: number of nodes in the network (N), node weight in kilometres for each intermediate node in a path, XPRO weight in kilometres for each additional XPRO that the data packet traverses on its path through an intermediate node, the maximum acceptable number of hops in a path (MH), maximum acceptable weighted path length in kilometres, the node configuration matrix and the link matrix.
- Step 2 : Assign a new source node and set all parameters to initial values. If all nodes have been assigned as source nodes then GO TO STEP MH+5.
- Step 3 : Find the next node that is directly connected to the assigned source node. If all nodes that are directly connected to the assigned source node have been found then GO TO STEP 2. Store the feasible path found together with its physical and weighted path lengths into the assigned source nodes temporary file. Assign the destination node of the feasible path found as "working node 1" (a reference node used as an intermediate node for the next feasible path).

Step 4 : Find the next node that is directly connected to working node 1. If all nodes that are directly connected to working node 1 have been found then GO TO STEP 3. Assign the node that is directly connected to working node 1 as working node 2. If the path found between the assigned source node and working node 2 is a feasible path then store the path information together with the feasible path physical and weighted path lengths in the assigned source node temporary file.

:
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:

Step K : Find the next node that is directly connected to working node (K-3). If all nodes that are directly connected to working node (K-3) have been found then GO TO STEP (K-1). Assign the node that is directly connected to working node (K-3) as working node (K-2). If the path found between the assigned source node and working node (K-2) is a feasible path then store the path information together with the feasible path physical and weighted lengths in the assigned source node temporary file.

:
:
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:

Step MH+3 : Find the next node that is directly connected to working node (MH-1). If all nodes that are directly connected to working node (MH-1) have been found then GO TO STEP (MH+1).

Assign the node that is directly connected to working node (MH-1) as working node (MH). If the path found between the assigned source node and working node (MH) is a feasible path then store the path information together with the feasible path physical and weighted lengths in the assigned source nodes temporary file.

Step MH+4 : GO TO STEP MH+3

Step MH+5 : Sort each node's temporary file of feasible paths in ascending order of weighted length and transfer sorted data to a permanent data file.

Step MH+6 : STOP

In the above program, MH is the maximum number of "hops" input by the routing manager and K is an integer that is greater than 4 but less than MH+3. In the context of the feasible path algorithm the "working node" is defined as the destination node of the last feasible path found from the assigned source node and is used as an intermediate node for the next feasible path from the assigned source node.

It is possible for the feasible path algorithm to be used by any general user who wishes to determine all paths between all possible node pairs within a network. The weighing factors in his network could be different to those defined in the examples shown in FIGURE 4(g) and in the case where, for example, the additional processing stages are not required then the input data would be such that the additional XPRO weight (XPROWT) and all entries of the node configuration matrix would be set to zero.

APPENDIX G

BEST ALTERNATIVE PATH ALGORITHM

The following is a basic outline of the program used to determine the best alternative paths between all node pairs within a network.

Program:

Step 1 : Initialize and set all parameters to zero.

Step 2 : Read in the node configuration matrix.

Step 3 : Read in the next feasible path. If all feasible paths have been read in then GO TO STEP 5.

Step 4 : If the primary hop of the feasible path between the source and destination node is an alternative to any of the previous path(s) found, then store path information together with the weighted length of the path in the data file.

However, in those cases where there are two possible alternative paths with the same primary hop and weighted length then the path with the least number of XPROS traversed at the intermediate node is stored in the data file. These are the best alternative paths.
GO TO STEP 3.

Step 5 : STOP

APPENDIX H

MODIFIED HEURISTIC ROUTING ALGORITHM

The basic outline of the modified heuristic routing algorithm used to determine the "optimal" routing tables for the network is as follows:

H.1 PROGRAM

- Step 1 : Set all parameters to their initial values.
- Step 2 : Read in the number of nodes, the number of links, path type, maximum acceptable utilization factor and whether the modified combination of paths is required.
- Step 3 : Read in the node configuration, link capacity and link matrices.
- Step 4 : Read in the high medium and low traffic-carrying nodes as well as their respective average-to-peak traffic ratios.
- Step 5 : Read in and store the traffic matrix in memory.
- Step 6 : Read in the best alternative paths for all source-to-destination node pair combinations. If the path type requested is the "shortest path" then store the first alternative path (lowest weight length path) as the primary path, the second as the secondary path, etc for all source to destination node pair combinations. Store these paths in their respective files, print-out the results then GO TO STEP 12. If any path type

other than the shortest path is selected then store in memory all the best alternative paths read in.

Step 7 : Start Primary Path Algorithm (see section H.1.1) to determine primary paths between all node pairs.

Step 8 : Read in all combinations of one link down from each node in the network and start the Secondary Path Algorithm (see section H.1.2) to determine all the secondary paths between all node pairs.

Step 9 : Read in all combinations of two links down from each node in the network with more than two links and start the Tertiary Path Algorithm (see section H.1.3) to determine all the tertiary paths between these nodes and all other nodes in the network.

Step 10 : Read in all combinations of three links down from each node in the network with more than three links and start the Fourth Alternative Path Algorithm (see section H.1.4) to determine all the fourth alternative paths between these nodes and all other nodes in the network.

Step 11 : Store the source to destination node path information for all possible node pair combinations in primary, secondary, tertiary and fourth alternative path files.

Step 12 : STOP.

In the following sections a more detailed explanation of the Algorithms mentioned in STEP 7 to STEP 10 is given

together with an explanation of a heuristic algorithm that is implemented where all the decision making is made for the choice of the primary, secondary, tertiary, and fourth alternative paths.

H.1.1 Primary Path Algorithm

Step 1 : Read in the best alternative paths.

Step 2 : For all possible source to destination node pair combinations, those source to destination paths that are directly connected and those paths that are connected via the lowest "weighted" distance (shortest paths) are stored in memory locations set aside for the "primary paths". (It is assumed that those paths which are directly connected have the lowest "weighted" distances and the next lowest "weighted" length paths are the paths with the least number of intermediate nodes. In the case of the example network shown in FIGURE 4(a) this assumption is true.)

Step 3 : Where there are two or more paths between a source-to-destination node pair that have an equal lowest weighted path length (connected with an equal number of intermediate nodes), then these paths are stored in memory locations set aside for "affected paths".

Step 4 : The end-to-end traffic is routed along those source to destination paths stored in memory locations set aside for "primary paths". This in effect assigns traffic flows f_i 's ($i=1,2,...P$), in both directions, across those links in the primary paths.

Step 5 : If there are any paths stored in memory locations set aside for "affected paths" then they are now considered and for each affected source to destination node pair, the best primary path is chosen by implementing the Modified Heuristic Algorithm detailed in section H.1.5 and these paths are then added to those paths stored in memory locations set aside for primary paths, otherwise the utilization factor and the traffic flow on each link is checked whether within limits (indication is given if they are not within the limits).

H.1.2 Secondary Path Algorithm

Step 1 : The end-to-end traffic is routed along those paths found in the "primary path algorithm" that, in effect, assign flows f_i 's ($i=1,2,\dots,P$), in both directions, across those links in the network utilized by these primary paths.

Step 2 : The link to be disconnected (information obtained from the link matrix) is read in and all those primary paths whose primary hops are affected by the disconnected link are stored in memory location set aside for "affected paths".

Step 3 : Those primary paths whose hops other than their primary hops (secondary, tertiary, etc. hops, that is, the second, third, etc. hop in a path) that are affected by the disconnected link are determined. The traffic flow that these paths generate is added to the total traffic flow that is required to flow over the direct path found in step 2.

- Step 4 : The traffic flow generated on each link (λ_i) by those paths saved in the memory location set aside for "affected paths" is removed from the network. This in effect produces new traffic flows accross some of the links in the network and zero traffic flow, in both directions, across the disconnected link.
- Step 5 : The affected paths are now considered and for each affected source to node pair combination the secondary paths are chosen from the best alternative paths by implementing the Modified Heuristic Algorithm.
- Step 6 : These paths are stored in a memory location set aside for secondary paths.
- Step 7 : The process is repeated until all links have been disconnected, in turn, and all secondary paths selected.

H.1.3 Tertiary Path Algorithm

- Step 1 : The end-to-end traffic is routed along those paths found in the "primary path algorithm". This in effect assigns flows f_i 's ($i=1,2,\dots,P$), in both directions, across those links in the network utilized by these primary paths.
- Step 2 : The next working node WN (defined here as a node in the network that has three or more other nodes connected directly to it) and two nodes connected directly to the working node, which represent the co-ordinates of the links to be disconnected, are read in.